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PLANETS

by Carl Sagan, Jonathan Norton Leonard
and the Editors of TIME-LIFE BOOKS

TIME-LIFE BOOKS NEW YORK

ABOUT THIS BOOK

THE SPACE AGE has given new impetus both to man's curiosity about the planets and to his need to know more about them. The techniques of modern astronomy are expanding planetary knowledge at an accelerating rate, and the day is approaching when man will visit other planets.

This book discusses, among other things, the many broad areas of disagreement that exist among astronomers regarding the planets' origin, composition, atmospheres and surfaces. It is concerned particularly with the possibility of life—no matter how primitive it may be—on other planets.

The text chapters are accompanied by picture essays, which are designed to be read independently or with the text. For example, Chapter 1, "The Discovery of the Solar System," surveys the evolution of man's thinking about the planets, while the picture essay, "Solving the Riddle of the Heavens," analyzes the changing concepts of the solar system.

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ON THE COVER

The 74-inch University of Toronto telescope is aimed skyward on a fine night for planet-watching. On the back cover, the nine planets appear in orbit. Reading outward from the sun they are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto.

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CONTENTS

INTRODUCTION 7

1 THE DISCOVERY OF THE SOLAR SYSTEM 8
Picture Essay: Solving the Riddle of the Heavens 16

2 THE MOST FAMILIAR PLANET 32
Picture Essay: A Space Visitor's View of the Earth 44

3 MEASURING THE DISTANT SPHERES 60
Picture Essay: The Tools of the Astronomer 68

4 THE LESSONS OF THE MOON 82
Picture Essay: The Earth's Companion 94

5 THE MYSTERY OF THE CLOUDED BODY 108
Picture Essay: Venus: Roasting under Ice 118

6 THE RED PLANET 130
Picture Essay: The Changing Image of Mars 140

7 A STRANGE VEILED GIANT 152
Picture Essay: Stormy Jupiter 160

8 THE SOLAR SYSTEM AND BEYOND 168
Picture Essay: Life on Other Worlds 180

The Solar System's Planets and Satellites 193
A Traffic Pattern for Planets 194
Further Reading and Acknowledgments 195
Index 196
Picture Credits 199

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INTRODUCTION

THIS BOOK appears at a time when the public is frequently reminded that our good earth is not alone. She is a member planet of the sun's family of nine. And that family, it now seems likely, may be only one of many—other families may belong to other stars; some might support life and civilizations totally different from but even more advanced than our own. More than philosophical interest is at stake, however. Expenses are being allotted and long-term national decisions are being made leading toward voyages to the moon and the planets. These decisions, to be responsible, require a wide diffusion of knowledge of the salient facts and understanding of the opportunities. Since 1958 and more especially since 1961, the entire nation has participated in the great venture and it must continually be reappraised.

The text of this book is lucid, the discourse concise and intelligent. The reader is made to share in the ever-questioning scientific process and is shown through examples how the fabric of science is woven and renewed—not unlike the replacement of cells in our body. By imparting to the reader the knowledge and conclusions of today, the book prepares him for the greater adventures of tomorrow.

—GERARD P. KUIPER
Director of the Lunar and Planetary Laboratory
University of Arizona

1

The Discovery of the Solar System

The members of the solar system are personified in this 17th Century German engraving.

ALL MODERN CIVILIZED PEOPLE know, or at least have been taught, that the solar system is a group of nine planets, four of them much bigger than the earth, held together by the gravitation of the sun in the center. The system is at least 10 billion miles in diameter, a distance hard to imagine but much smaller than the distance to the nearest star, which is 25,000 billion miles. Astronomers still disagree about how it was formed. Apparently it is about five billion years old and reached its present state not long after the sun condensed out of a great cloud of dust and gas.

This now-familiar picture is highly sophisticated, the product of thousands of years of human observation and thought. It is far from any commonsense conclusion that an intelligent but uninformed man could reach by viewing the heavens with his own eyes. For people who lived before the dawn of history, there was no such thing as a solar system. The world, as they understood it, was a small patch of land bounded by distant hills and perhaps by the blue line of the sea. Close overhead was the sky, and across it rode the beneficent sun, a god giving light and warmth. The moon was a lesser god shining with paler light, and with it at night rode the brilliant innumerable stars. Outside this little universe lay unimagined mystery.

But as human thought grew and improved, it gradually acquired the quality of wonder. A few inquiring minds began to speculate about the drama of the sky. Why did the sun rise at different places? Why did the moon change its shape and sometimes shine wanly by day? Why did a few of the stars—planets—move among the others? Did such things have causes? Did they have meanings for men?

The first astronomers watched the sky and made crude observations. They numbered the days between full moons, and the days in a year. So started an ambitious program of scientific research: the attempt to understand the solar system. It continued for thousands of years, brought practical benefits and intellectual triumphs, caused furious controversies and repeatedly changed man's view of his place in the universe.

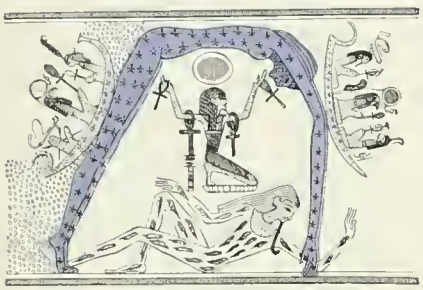
The ancient research program is not completed yet, though the solar system has grown enormously in men's eyes, both in size and in interest. Within the last few years the pace of discovery has gathered speed and it is now approaching a climax. Spaceships loaded with delicate instruments have been leaving the earth to study the moon and planets close-by. Soon they will land on some of them, and living men will follow.

Both instruments and human explorers are sure to find many surprises, but the greatest prize they seek is life beyond the earth. Most scientists agree that life will appear spontaneously in any place where conditions remain sufficiently favorable for a very long time, but this conviction is based on inferences and extrapolations. They do not know just what conditions are necessary to give birth to living organisms. Some think that the laws of chemistry and physics permit only one broad kind of life. If this is true, all living things that may be found anywhere in the universe will be in a chemical sense distant relatives of man, descended from the same kinds of complex molecules. Made of the same materials and

initiated in similar environments, extraterrestrial organisms may be roughly similar to life on earth, in chemistry if not in form. Another view is that many different sets of conditions can produce life, and all such utterly alien organisms will be man's relatives only in the sense that they are alive.

The exploration of the solar system will not answer all questions that can be asked about life, but the first trace of any living organism—or of life now extinct—found on the moon or a planet will cause the highest excitement in the history of science, and the research problem started so long ago will have changed once again man's view of his place in the universe.

This book will sketch briefly the history of the solar system as it grew and took shape in man's understanding and will give the latest information and theories about it, with special emphasis on the planets as places, each with its own characteristics such as surface features, atmosphere, temperature and internal conditions. Each of the nine known planets has its history, which may cast light on the general evolution of planets from the time of their original formation. The moon and other planetary satellites will be included, but the sun will not be described except as a source of light, heat, gravitation and charged particles. Some theories will be presented that seem unlikely at first glance. To consider such theories is only prudence. In astronomy unlikely theories have often proved correct while the commonsense views, including those of genuine experts, have often proved wrong.



THE EGYPTIAN COSMOS was encompassed by the sky goddess Nut, the star-studded figure at top; early Egyptians believed she swallowed the sun each evening and returned it each morning. Beneath Nut is Shu, the god of air, shown holding symbols of immortality in his hands, and under him lies the earth god Geb, his body covered with leaves. The boats on each side of the drawing carried the sun on its journey across the sky

The ancients' earth-centered universe

For centuries educated people have known that the sun is by far the biggest member of the solar system and stands near its center. Around it the nine planets are arranged in the following order: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto. But to the first truly civilized men—such as the ancient Egyptians and Mesopotamians, who were just as intelligent as modern men—the earth appeared flat and solid, and obviously the principal thing in the universe. They knew no reason to think otherwise. They accepted the sun, moon, planets and stars for what they looked like and used their motions as a valuable means of predicting the future.

Prediction of this kind had a successful history. Long before the invention of writing, astronomer-priests kept track of the sun's annual north-and-south motion and connected it correctly with the progress of the seasons on the earth. The priests watched the sun, counted the days after its farthest retreat toward the south and predicted, as if a dependable god had told them, when life-giving floods would sweep down the rivers.

The system worked because floods depend on the seasons, which in turn depend on the sun. The earth's axis of rotation points in such a way that as the earth sweeps around its orbit, each hemisphere, north or south, gets more than its share of sunlight for six months, causing the

alternation from summer to winter. Relating the ocean tides to the moon's apparent changes of shape worked well too, because the moon through its gravitational pull is really the principal cause of the tides. So it was only natural for the astronomer-priests to become convinced that the five "stray sheep"—the visible planets Mercury, Venus, Mars, Jupiter and Saturn—that move in relation to the other stars also had power over earthly affairs. If the sun could bring summer and winter and the moon move the oceans, why shouldn't Mars and Venus have effects on lesser matters such as human wars?

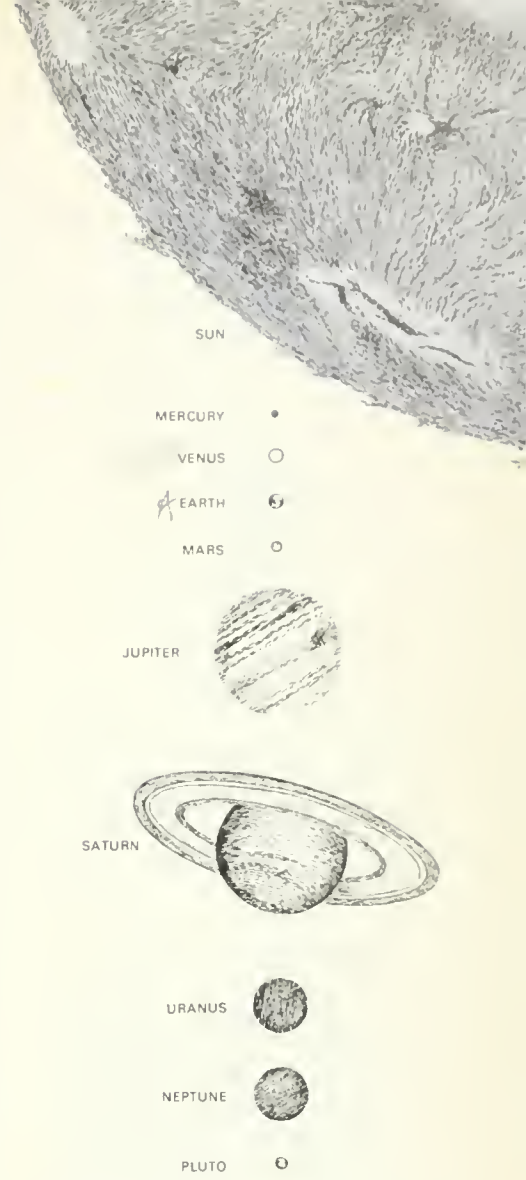
Astrology: predictions from the planets

Out of this wrong but natural conviction grew astrology, the prediction of the future by means of the stars. For astrologers, "the stars" meant principally the planets, the real stars acting as a background. To perform their duties properly the astrologers wanted to know the positions of the planets at specified times in the past and future. This called for careful observation and faithful record-keeping. The best work was done in Mesopotamia, where astronomical records were kept with surprising accuracy as early as 4,000 years ago. Since most events in the heavens repeat themselves, the astrologers could tell by consulting their records where the planets would be when a king planned to launch an attack on a neighboring state. If they decided that the position of Saturn or Mars—the war planets—would be unfavorable, they might advise the king to hold off until the prospects improved.

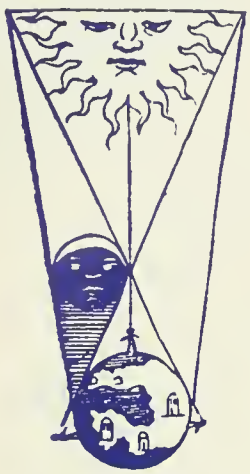
This sort of counseling gave the astrologers great economic and political power. Their importance reached its peak in Babylonia 1,000 years before the birth of Christ, where they formed a noble caste whose members had to be physically unblemished and of pure-blooded ancestry. The influence of these haughty aristocrats of mysterious learning reached throughout the ancient world. They are mentioned frequently in the Bible. The Three Wise Men of the East who were led to Bethlehem by a star were almost surely astrologers from Mesopotamia, and the gold, frankincense and myrrh they brought for the infant Jesus were meant at the time to be understood as a sign that they believed the birth to be a great event.

The astrologers learned to forecast lunar and solar eclipses, which were considered important omens. They used only their records and had no notion of the way that the earth casts its shadow on the moon, or the moon passes between the earth and the sun. Explanations of such matters were left for the Greeks, who were the first to progress beyond incurious observation and seek rational explanation.

The Greeks wasted little effort on astrology and as early as 600 B.C. were showing a novel distaste for easy reliance on the supernatural. Greek astronomers believed that the true nature of the heavenly bodies could be revealed by imagining mechanisms that would make them move as they appear to do. In modern scientific jargon this is called "constructing a model." It can be done badly, and the Greeks' models were bad by



THE RELATIVE SIZES of the planets are illustrated here. Mercury, Venus, Earth and Mars, the four closest to the sun, are called terrestrial, or earthlike, planets because of their similarity in size and density. The next four planets—Jupiter, Saturn, Uranus and Neptune—are classed as Jovian, or Jupiterlike. While they are much larger than the terrestrial planets, their densities are considerably less. Little is known about Pluto, the most distant of the planets, but it is thought to be terrestrial.



A SOLAR ECLIPSE, viewed from three positions on the earth, is accurately explained in this 16th Century Italian woodcut. To the little man at left, the sun is obscured by the moon *(center)* and the eclipse is total. To the man at the top of the globe, the eclipse is partial as the moon partly blocks his view The man at right sees no eclipse at all.

THE EARTH'S ROUNDNESS is demonstrated, as this 16th Century Italian drawing shows, by the way a departing ship seems to sink below the horizon From the tower *(left)*, the view is gradually blocked by the curvature of the earth as the ship sails away As far back as ancient Greece, this phenomenon was correctly attributed to the roundness of the earth

modern standards, but it is a legitimate and often very effective scientific approach.

Most of the models the Greeks constructed to explain the solar system held that the sun, moon, planets and stars are kept from falling by invisible, concentric spheres or circles that rotate and carry them around the earth at different speeds. For reasons that do not impress modern minds, the Greeks admired spheres and circles, which they considered noble shapes that must be used exclusively in astronomy. This curious fixed idea caused immediate trouble, because the heavenly bodies do not follow circular courses, either in fact or appearance. As viewed from the earth, the planets move at varying speeds, sometimes seeming to turn backward, and wander over the sky in such a complicated way that no single set of spheres could begin to account for their behavior.

Later Greeks tried to overcome this difficulty by adding secondary spheres attached at varying angles to the primary ones. A planet carried along on a secondary sphere would appear to follow a noncircular course that might resemble its observed motions. But two spheres per planet were not enough. Eudoxus of Cnidus (409-356 B.C.) was driven to use 27 spheres. His successors used as many as 57, but even this geometrical nightmare did not work quite correctly.

Ptolemy's persistent mistake

The most famous Greek theory is that of Claudius Ptolemy, a Greek who lived in Egypt in the Second Century of the Christian era and may have merely recorded the ideas of others. It has still more complications and does not adequately explain facts such as the planets' periodic changes of brightness, or give their distances from either the earth or the sun. Critics no doubt pointed to these defects at the time, but Ptolemy lived when Greco-Roman civilization was past its creative prime. His system triumphed largely because it was the last. Transmitted by the Arabs to medieval Europe as the Almagest (which means "The Greatest" in garbled Greek), it finally acquired the force of religious dogma and might not be questioned without danger of heresy. This was unfortunate, because Ptolemy was not the best example of Greek clear thinking.

The Greeks early discarded the "commonsense" idea of a flat earth, reasoning that it must be round because of the circular shadow it casts on the moon and the way that ships seem to sink below the horizon of the sea. One inspired astronomer, Aristarchus of Samos, argued in about 275 B.C. that the sun, not the earth, is the center of heavenly motions. He also believed that the sun was bigger than the earth. We do not know today how he reached these modern-sounding conclusions; both were rejected in his time as fantastic.

Another Greek realist, Eratosthenes, estimated the size of the earth and got a surprisingly good answer. The earth's circumference came out as 250,000 stadia, a contemporary unit of length. Since the exact length of the stadium that he used is not known, his accuracy cannot be checked, but he was probably not more than 6 per cent off. Much of the best work

of the Greeks was not appreciated until comparatively modern times, and almost the only astronomical information that they transmitted to medieval Europe was contained in Ptolemy's elaborate, impressive but misleading Almagest. After Ptolemy came nothing of astronomical consequence for more than 1,000 years. During the long ages of ignorance that followed the decline of the Greco-Roman culture, astronomy remained dormant. Until late in the Middle Ages the few learned men of Christian Europe paid almost no attention to the sky. They did not even record the supernova, or exploding star, of 1054 A.D., which Chinese astronomers reported shone brighter than all the other stars; its remains can now be seen as the famous Crab nebula.

When European science began to stir after its long coma, the most imposing book available on astronomy and related matters remained the Almagest. In spite of its faults the work must have been a delightful revelation for scholars who had been concentrating almost exclusively on theological trivia. Its mathematics was far beyond anything known in backward Europe, and it also described Greek astronomical instruments. Medieval Christians began, timidly at first, to make and use copies of them.

So Ptolemy had a second heyday in the 15th Century, but science was on a rising curve, not on a decline as in Ptolemy's own day. Along with its reverence for the past, it was beginning to show sparks of independent thought. Western European scientists took more interest in observation and experiment than the Greeks had, and depended less on unsupported ideas. While they still believed in the Ptolemaic system, 15th Century astronomers built observatories, improved Ptolemy's instruments and devised novel ones. Their observations made Ptolemy's system look worse and worse.

Criticism of Ptolemy was increasing but seldom voiced, because Western Europe had an institution unknown to the Greeks: a powerful religious bureaucracy that tried to silence anyone who differed with its official beliefs. One of its dogmas insisted that the earth must remain the large central body of the universe. This misconception is the main reason why the Ptolemaic system encountered difficulties, but anyone who pointed this out was headed for trouble.

PRIMITIVE ASTRONOMY is reflected by this drawing, discovered on the wall of an Indian cave in Arizona, and believed to have been inspired by the famous supernova, or exploding star, of 1054. The supernova did not pass between the earth and the crescent moon, but the Indians may have shown it this way because they observed that the exploding star outshone the moon. The only other record of the great cosmic event was left by Chinese astronomers. Europeans ignored it.

The great Copernican revolt

The break with the past was finally made by the Polish astronomer Nicolaus Copernicus. He prudently did not publish his great treatise, "On the Revolutions of the Heavenly Bodies," until just before he died in 1543.

The chief innovation of Copernicus was to consider the sun the center of the solar system, just as Aristarchus had done 1,800 years before. He arranged the earth and the five planets then known in the proper order —Mercury, Venus, Earth, Mars, Jupiter, Saturn—and put them on circular orbits around the sun. The circles were a mistake, but the sun-centered system was simpler than its predecessors, and it explained better

than they did the observation of planetary motions since Ptolemy's time.

Copernicus made no mistake in keeping his ideas out of sight. Europe was in the midst of the wars of religion, and ideological violence was commonplace. His book was fiercely attacked by conservative churchmen. On a lower intellectual level, many people of the time were outraged by the demotion of the great earth, the habitat of God-favored men, and felt that they, personally, had been demoted with it. They reacted much as people did 400 years later when they angrily opposed Darwin's theory of evolution (some still oppose it) because it made man a flesh-and-blood relative of the lower animals. One follower of Copernicus, the great physicist Galileo, was silenced by the Church because of his belief that the earth moves around the sun. Another, Giordano Bruno, was burned at the stake by the Inquisition. Copernicus' work was put on the Church's Index of forbidden books, from which it was not removed officially until 1757.

Kepler's demotion of the earth

But in spite of conservative resistance the essential ideas of Copernicus were gradually accepted by Europe's men of learning. The earth became just one of the members of the sun's entourage. This was a revolutionary change in man's thinking about himself and the universe.

The Copernican system had serious faults, and one of the astronomers who did not accept it was Tycho Brahe, a Dane who was the best observer of the time and had the best observatory. For a lifetime he worked to overthrow Copernicus by devising a better system, and he failed chiefly because he restored the earth to its central position. When he died in 1601, he left his massive and meticulous records to his young assistant, Johannes Kepler, and trusted him to carry on the work.

Perhaps Kepler tried for a while to demolish Copernicus, but his study of Tycho's excellent records soon forced him to even more radical innovations. He not only placed the sun near the center of the solar system but also concluded by brilliant intuition that it somehow provided the motive power for planetary movements. He did not follow up this hint of gravitation. His greatest discovery was that the planetary orbits are ellipses, a specific kind of closed oval curve, not the noble circles that the Greeks and his own contemporaries, including Copernicus, all considered necessary.

Kepler found by carefully studying Mars that its motion can be understood if its orbit is assumed to be an ellipse. The orbits of the moon, earth and the other planets proved to be ellipses too, though most of them are nearly circles. There was no need for an intricate maze of interrelated circles; just a single ellipse for each object. Kepler had achieved a great simplification, which is a kind of triumph that scientists celebrate with special rejoicing.

But Kepler had not answered the age-old question, "What holds the planets up and makes them move on their courses?" He abolished the invisible spheres of the Greeks, which after millennia had acquired a

sort of spurious reality, but put nothing in their place. This would have to wait for Isaac Newton, who was not born until 1642.

When he was only 23, Newton retired to rural England to avoid a pestilence in London and began to think about the moon and the mysterious force that keeps it orbiting around the earth. It does not fly off into space, and it does not fall to earth like lesser, nearby objects. There must be some general principle behind this behavior.

The moon as a falling body

Newton did not discover gravitation by watching an apple fall or by being hit by one, as in popular legend. Laws relating to falling objects had been studied extensively, but they had been applied only on the surface of the earth. There was no idea of gravitation as a universal force that affects all objects wherever they may be. Obviously, said the reasoning of the time, it does not apply to the heavenly bodies, since they do not fall to the earth. Newton showed his genius by applying the laws of falling bodies to the unfalling moon.

He knew from observation that an object thrown horizontally follows a curve whose flatness increases with the speed. He reasoned that perhaps the high speed of the moon, about 2,300 mph, might be just enough to make it follow its known orbit in spite of its tendency to fall like other objects. Making an educated guess based on the mathematical properties of Kepler's ellipses, he assumed that as the distance from the earth increases, the force of its gravitation diminishes in proportion to the square of the distance.

Newton's first attempt to try this idea on the moon was not entirely successful, but when he got a better estimate of the earth's size it worked admirably. The moon actually moves at just the right speed for the earth's gravitation, weakened by distance, to keep it in its orbit. Newton had done an extraordinary thing, one of the greatest feats in the history of thought. He had used the familiar force that makes things fall to earth to explain why some do not.

With Newton, the framework of the solar system took its modern form, free of the mysticism of earliest times and the rational but nonexistent transparent spheres of the Greeks. All its members move in response to Newton's universal force of gravitation, whose action is given in a single sentence: "Bodies attract each other with a force that varies directly as the product of their masses and inversely as the square of the distance between them." As to why Newton's law works, most scientists feel that this is a meaningless question. It happens that the universe is so made that Newton's law provides an excellent summary of the observed motions. There may be no deeper truth to it than that.

After Newton, the ancient research program entered a new phase. The baffling central mystery had been dispelled; the mechanics of the solar system was well understood. Now its fascinating members, the earth's near neighbors in the universe, could be examined and later explored in detail.

A GREAT PLANET-WATCHER, the 16th Century Danish astronomer Tycho Brahe lived before the invention of the telescope. He made his observations with the naked eye, and recorded precise data on the motions of planets. Tycho concluded from his observations that the sun and moon revolved around the earth *(black)*, while Mercury, Venus, Mars, Jupiter and Saturn—the planets known to Tycho—circled the sun. Fortunately, his records were inherited by the great astronomer Johannes Kepler, who used them to help achieve an explanation of planetary motions similar to that held today

Solving the Riddle of the Heavens

From the beginnings of history, the heavens have fascinated and challenged thoughtful men. As long ago as 3000 B.C. myths were invented to explain the origin and arrangement of the solar system as the feat of awesome gods. Later, the heavenly bodies—the sun, moon, stars and planets—were given human or animal identities and mystical qualities.

Then, some 26 centuries ago, myth and symbolism began to give way to careful observation and calculation as more painstaking investigators sought the truth about the heavens, often resorting to ingenious theories to overcome huge gaps in their knowledge. It was not until 1512, when Copernicus placed the motionless sun at the center of the solar system, that astronomy was freed of its biggest misconception—that all other heavenly bodies revolved around a stationary earth. In the next 200 years, the workings of the solar system, including the orbital paths of the visible planets, were correctly determined. But even today the origin of the solar system remains a riddle. Despite increasingly sophisticated tools and techniques, the astronomer must use his imagination for leads—just as he has for centuries.

THE HEAVENLY PANOPLY

The heavens, observed in ancient times, seemed to be a moving spectacle above a motionless earth that occupied the center of the universe. The moon's phases and the apparently looping path of a planet were recorded over many nights, as was the sun's "movement" through the day sky, long before men understood the relationships of the different heavenly bodies to one another.

The Sumerians' Universe

The first recorded attempt to explain the creation and composition of the heavenly bodies was made by Sumerians in the Third Millennium B.C.

The Sumerians, who inhabited a 300-mile-long realm between the Tigris and Euphrates Rivers, gave to civilization the wheel, the plow and cuneiform writing. As befitted such innovators, they had a conception of the universe both realistic and imaginative: a sea-girt hemisphere *(below)* in which the heavenly bodies clustered in the wind above the familiar water and earth. According to Sumerian mythology, these elements were governed by the gods of creation *(right)*—giants in human shape.

THE SUMERIAN CREATION
Creating the universe, the great Enlil, Sumerian god of air, is shown wrenching apart the mountain containing both heaven and earth. According to myth, the figure in the upper portion of the mountain is Enlil's father, the god of heaven, the figure in the base is his mother, the goddess of earth. The original mountain was said to have risen from the boundless eternal sea.

A TIN-ROOFED UNIVERSE
The Sumerians visualized the universe as a flat earth topped by the tin vault of heaven. Between them was the swirling atmosphere, in which the glowing sun, moon, planets and stars were controlled by the manipulations of the gods. Other early civilizations, like the Babylonian and Egyptian, modified the Sumerian concept, but accepted its supernatural premise.

A WATERY UNIVERSE
The earth, according to Thales, was a flat disk floating on the eternal water from which it had emerged. He saw water as the source of all things. He noted that it nourished life on earth and concluded that the heavens—where rain originates—must be made of evaporated water. Not only did water surround the earth but it also rimmed the heavenly vault, a vast hemisphere containing the sun, moon, all planets and stars. Thales made his deductions from simple and seemingly reasonable observations, and invoked no gods to explain his universe.

The Novel Theories of the Greeks

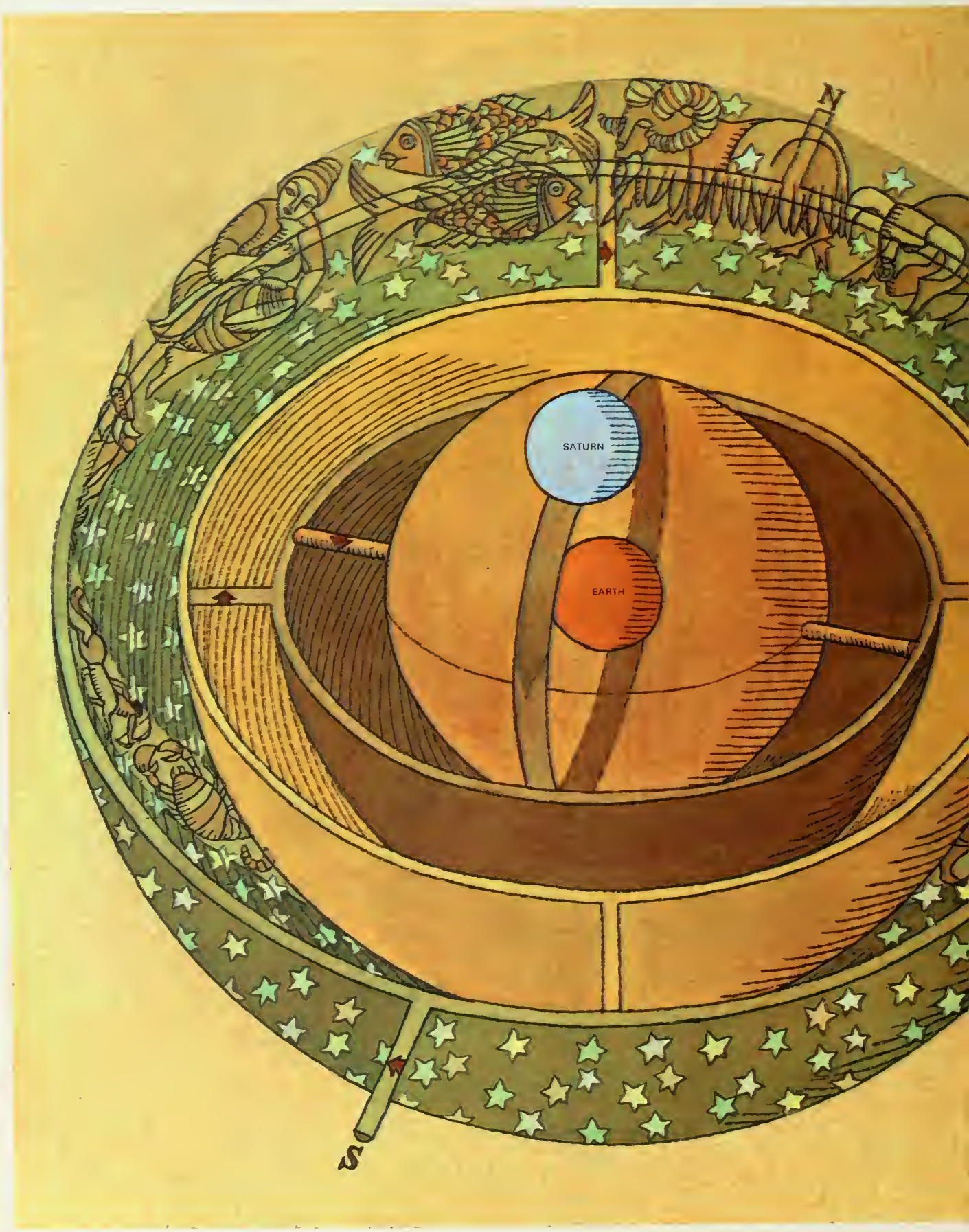
Greek philosophers subjected earlier myths concerning the universe to painstaking inquiry. Because they sought a "first principle" as a basic cause of all phenomena, the Greeks came up with some imaginative, if inaccurate, explanations of the universe. In the Sixth Century B.C. the philosopher Thales reasoned that water must be the raw material from which the universe was produced *(above)*. Anaximander, a friend of Thales, held that the universe began with a sphere of fire enclosing a cold, moist mass, from which it was separated by a layer of mist. Eventually, the cold mass became the earth, the fire became the light of the heavenly bodies, and the mist the surrounding atmosphere *(right)*.

In the Fifth Century B.C., Philolaos adopted a radically different approach. Believing the number 10 signified perfection, he presupposed a universe of 10 heavenly bodies. Since only nine—five planets, the sun, the moon, the earth and the sphere of the stars—were visible, a tenth, the counterearth, was invented. Arbitrary as this system was, it was the first to picture the earth as a revolving sphere like other planets *(opposite)*.

ANAXIMANDER'S FIERY RINGS
At the center of Anaximander's universe, which sprang not from any single element but from what he called a "germ" of fused opposites, was a free-floating earth shaped like a drum. Surrounding it were fiery rings enclosed in mist through which the heavenly bodies rolled, appearing through openings in the mist. Anaximander placed the "cooler" stars nearest the earth. Beyond the moon and sun the fiercest fires burned—a fiery sphere about the universe.

PHILOLAOS' CIRCLING SPHERES

In the revolutionary design of Philolaos, the earth appears as a sphere and no longer occupies the center of the universe. Instead a "central fire" burns at the core and illuminates the sun. Between this fire and the earth, a protective counterearth revolves, invisible from the hemisphere where all the earth's population was thought to live. The heavenly bodies, including the five other known planets, revolve on circular paths within an envelope of fire.


N
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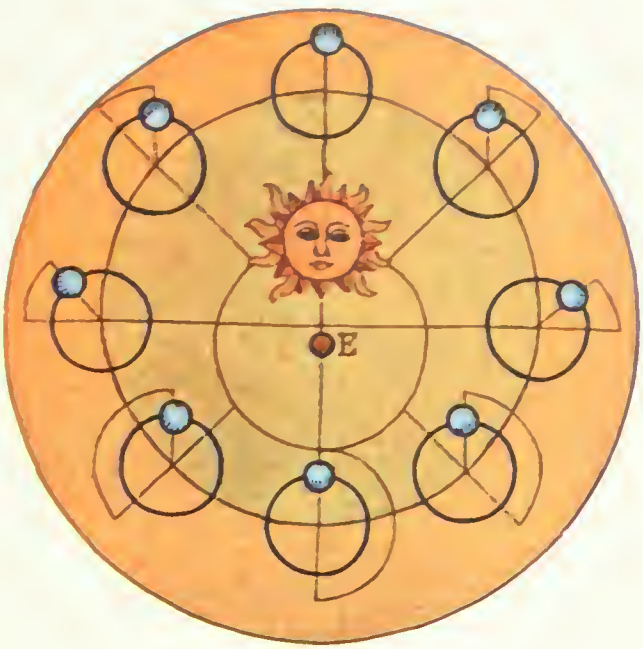
A System of Circles and Spheres

Early Greek philosophers pondered the universe with little more than their logic and eyesight to help them. But later Greeks applied maturing mathematical skills to the problem of heavenly movements. As early as the Fourth Century B.C., Eudoxus sought a formula to explain what appeared to be looping planetary paths *(below)*. Believing that planets orbited the earth in perfect circles, Eudoxus drew 27 concentric spheres around the earth. Each sphere, and any bodies within it, was calculated to rotate on a different axis. Eudoxus could approximate the motions of any heavenly body by combining the movements of these spheres *(left)*.

But Eudoxus' clever theory left unexplained why planets dimmed and grew bright, indicating variations in their distance from the earth. In the First Century A.D. the astronomer-cartographer Ptolemy devised a system in which planets revolved in small circles while orbiting the earth *(right)*. Thus, Ptolemy "proved" that a planet might be close to the earth at one sighting and distant at another, while its principal motion remained a circle around the earth.



CIRCLES IN THE SKY
Saturn's fading and brightening were accounted for by Ptolemy, who devised the scheme shown above. Saturn orbits the earth and at the same time rotates in a smaller circle—hence the changes in its distance from earth. The sun, according to Ptolemy's system, described a simple and regular orbit around the earth. Ptolemy's theory was not refuted for 15 centuries.

LOOPING THE LOOP
Saturn's looping path *(above)*, traced over a three year period as it crosses the constellations of Pisces and part of Aries—one ninth of the heavenly zodiac—was explained by Eudoxus by means of the chart at left. Not only did he have Saturn *(blue)* describing a circular orbit around a central earth, but the inner sphere in which it orbited was itself revolving on an axis attached to a revolving outer sphere. Four such spheres were needed to explain Saturn's twists as seen from the earth, and 27 spheres supposedly produced the motions of the whole solar system. The outermost sphere, which rotated around the earth daily, contained the stars on which are superimposed the symbolic figures of the zodiac.

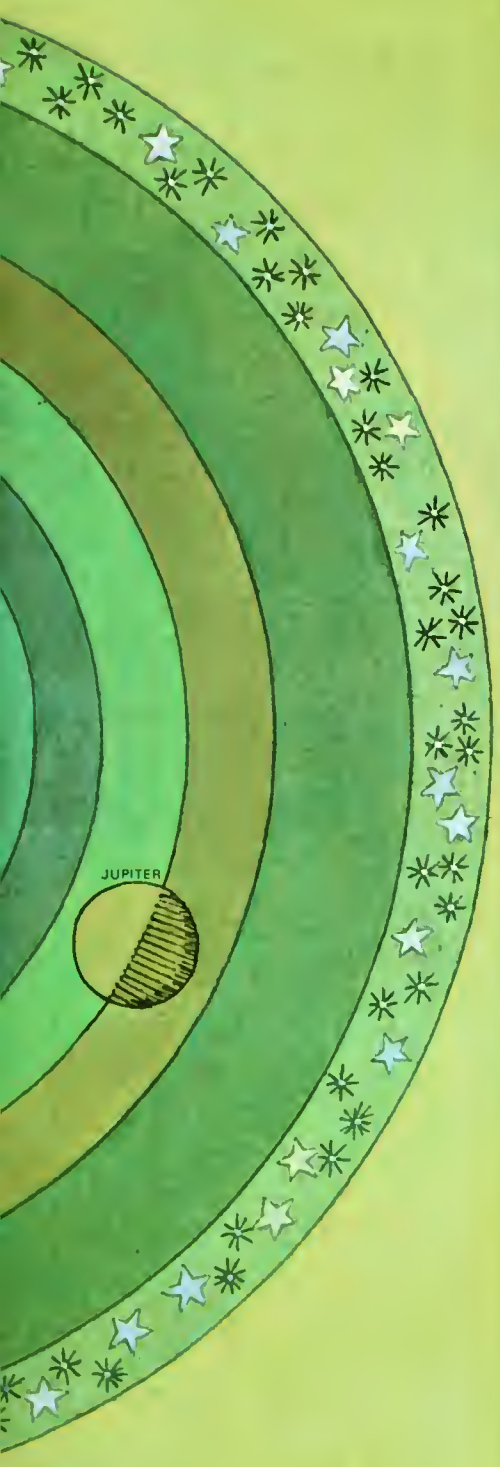
The Sun Stops Moving

"Although the idea seemed absurd," wrote the famous 16th Century Polish astronomer Nicolaus Copernicus, "I began to think of a motion of the earth." Once it was assumed that the earth itself rotated each day—rather than having all the other heavenly bodies rush around the earth every 24 hours—the motions of the planets, said Copernicus, became more comprehensible.

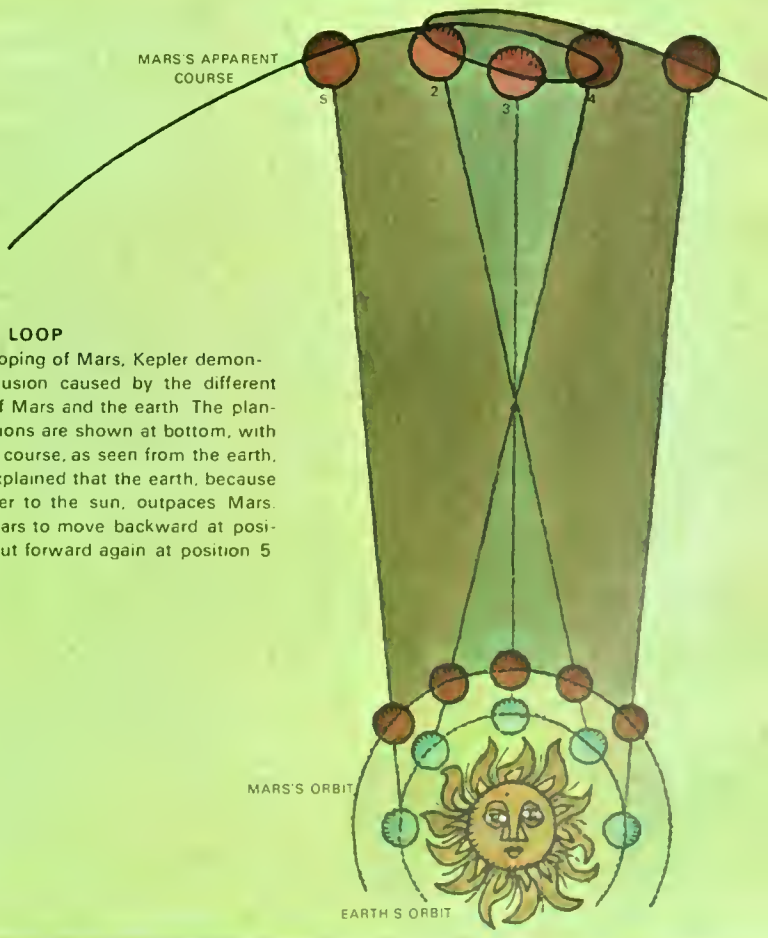
Having challenged the established notion of a fixed earth, Copernicus ventured further. In 1512 he put the sun, instead of the earth, at the center of the solar system *(right)*. However, he still believed that the planets orbited in perfect circles.

It was not until 1609 that the German astronomer Johannes Kepler described planetary paths correctly for the first time. Agreeing with Copernicus that the planets were sun-centered, Kepler began to question the notion of circular orbits. His calculations, based on voluminous and precise observations, indicated elliptical orbits instead. Proceeding on this assumption, Kepler then proved that the speed of a planet depends on its distance from the sun *(opposite, top)*. This finding, broadened by Newton into his gravitation law, ended, once and for all, the age-old speculations on the motions of the solar system.

CIRCLING THE SUN
At the center of Copernicus' planetary system *(right)* is the sun, "sitting on the royal throne." The earth together with its satellite, the moon, was but one of six known planets that circled the sun. Copernicus placed the planets in their proper sequence for the first time—Mercury and Venus between the sun and the earth; Mars, Jupiter and Saturn between earth and stars.



CHANGING SPEEDS IN ORBIT
Orbiting in its elliptical course, Mars speeds up when near the sun (perihelion) and slows down farther away (aphelion), taking the same time to cover the two different distances shown. Kepler proved that all planets described such elliptical orbits.



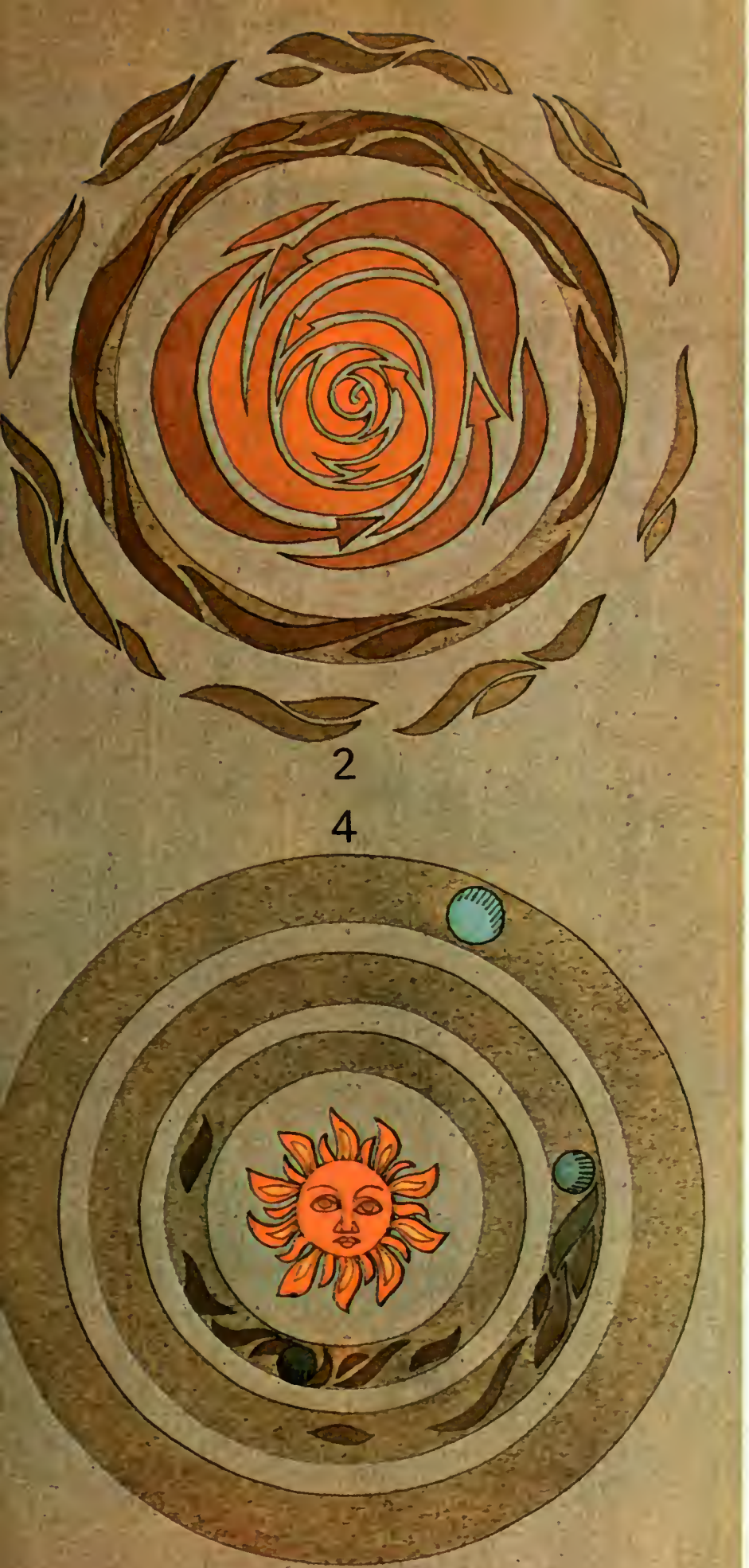
AN ILLUSORY LOOP
The apparent looping of Mars, Kepler demonstrated, is an illusion caused by the different orbital speeds of Mars and the earth. The planets' actual positions are shown at bottom, with Mars's apparent course, as seen from the earth, at top. Kepler explained that the earth, because its orbit is nearer to the sun, outpaces Mars. Thus Mars appears to move backward at positions 3 and 4, but forward again at position 5.

Planets from a Cloud of Gas

Even though Copernicus and Kepler correctly arranged the solar system, the mystery of its beginnings still defies solution. Curiously, it was not an astronomer but the great German philosopher Immanuel Kant who first propounded in 1755 the most enduring and renowned of all scientific theories seeking to explain the origin of the solar system—the nebular hypothesis.

According to Kant, the solar system was developed from an enormous cloud, or nebula, of gas. Kant thought of this cloud as having been originally cool and motionless. The particles in it were pulled together by their gravitational attraction for one another, and somehow began rotating in a common direction. As this nebula became more compressed, Kant said, it grew hotter and hotter, until it glowed into a giant primitive sun. As the sun contracted, Kant suggested, its rate of spin steadily increased until it finally cast off the gaseous rings from which the planets were formed, one at a time.

In 1796 the French scientist Pierre Simon, Marquis de Laplace, independently advanced a hypothesis similar to Kant's. The main difference was that Laplace thought of the gaseous nebula as heated and rotating from the very start. A better mathematician than Kant, he knew that the mere act of condensation could never have started such a nebula rotating. Although some of the details in the Kant-Laplace nebular hypothesis have been modified over the years, its principle is still accepted today.



1 A GASEOUS NEBULA

A vast, hot, slowly rotating nebula of gas forms the first stage in Laplace's hypothesis of how the solar system began. As it rotated, the outer regions of the nebula began to cool. Laplace thought the original size of this primeval gaseous globe must have been larger than the dimensions of the solar system he knew—i.e., to the orbit of Uranus. Beyond lay the stars.

2 THE EJECTED RINGS

In the second stage the rotating mass contracted, meanwhile spinning with increasing velocity. Just as mud is thrown off the rim of a swiftly spinning automobile wheel, gaseous rings were ejected from the main body. In this drawing, a newly separated ring is shown just outside the whirling core. Beyond it, a previously ejected ring is beginning to break up into clouds of gas.

3 THE FORMING PLANETS

The solar system begins to take shape as the clouds of gas condense and recombine. This condensation process has already produced the round shape of a planet, and another gas ring is shown gathering into whorls which, as they cool, will also form a planet. The core of the shrinking nebula, still ejecting its rings of matter, is beginning to resemble the familiar sun.

4 A SYSTEM IN SPACE

A stable sun, throwing off no more rings, is surrounded by fully formed embryonic planets in the concluding stage of the Kant-Laplace hypothesis. The planets shown closest to the sun—Mercury, Venus and the earth—are the last to condense. The planets are already circling the sun in orbits corresponding to their former rings, in the same direction as the sun's rotation.

A Tide of Gas Torn from the Sun

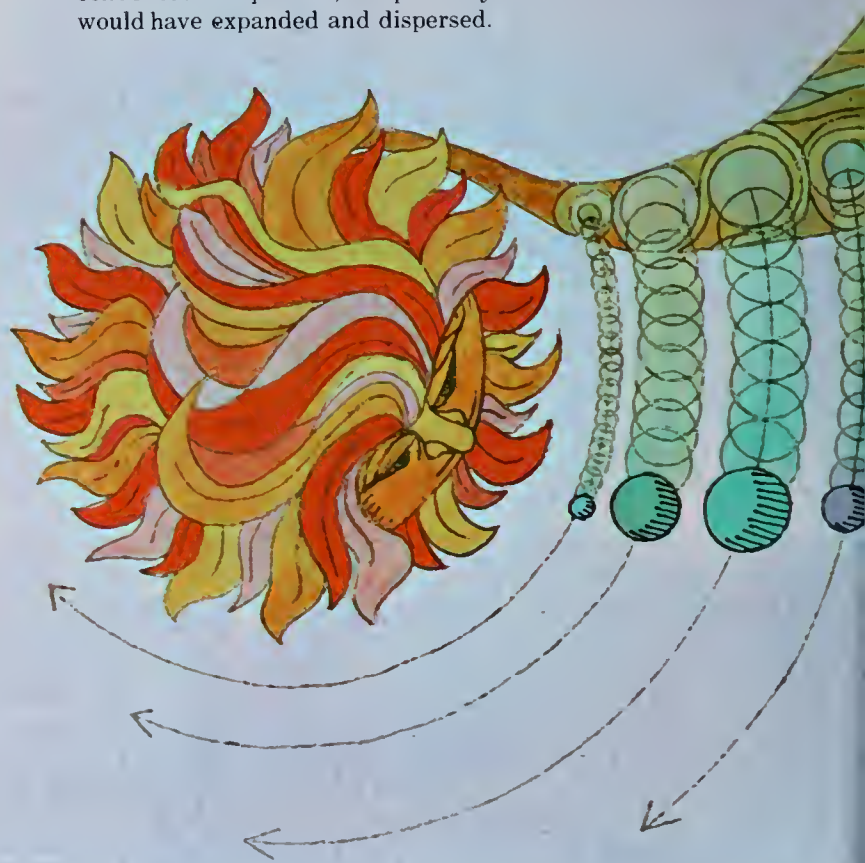
Not until the 20th Century did a theory on the origin of the solar system seriously challenge the Kant-Laplace nebular hypothesis *(pages 26-27)*. Proposed by Sir James Jeans in 1901, the tidal theory avoided the unanswered problem of how the nebula had begun to spin and appeared to explain *(right)* the planet sizes.

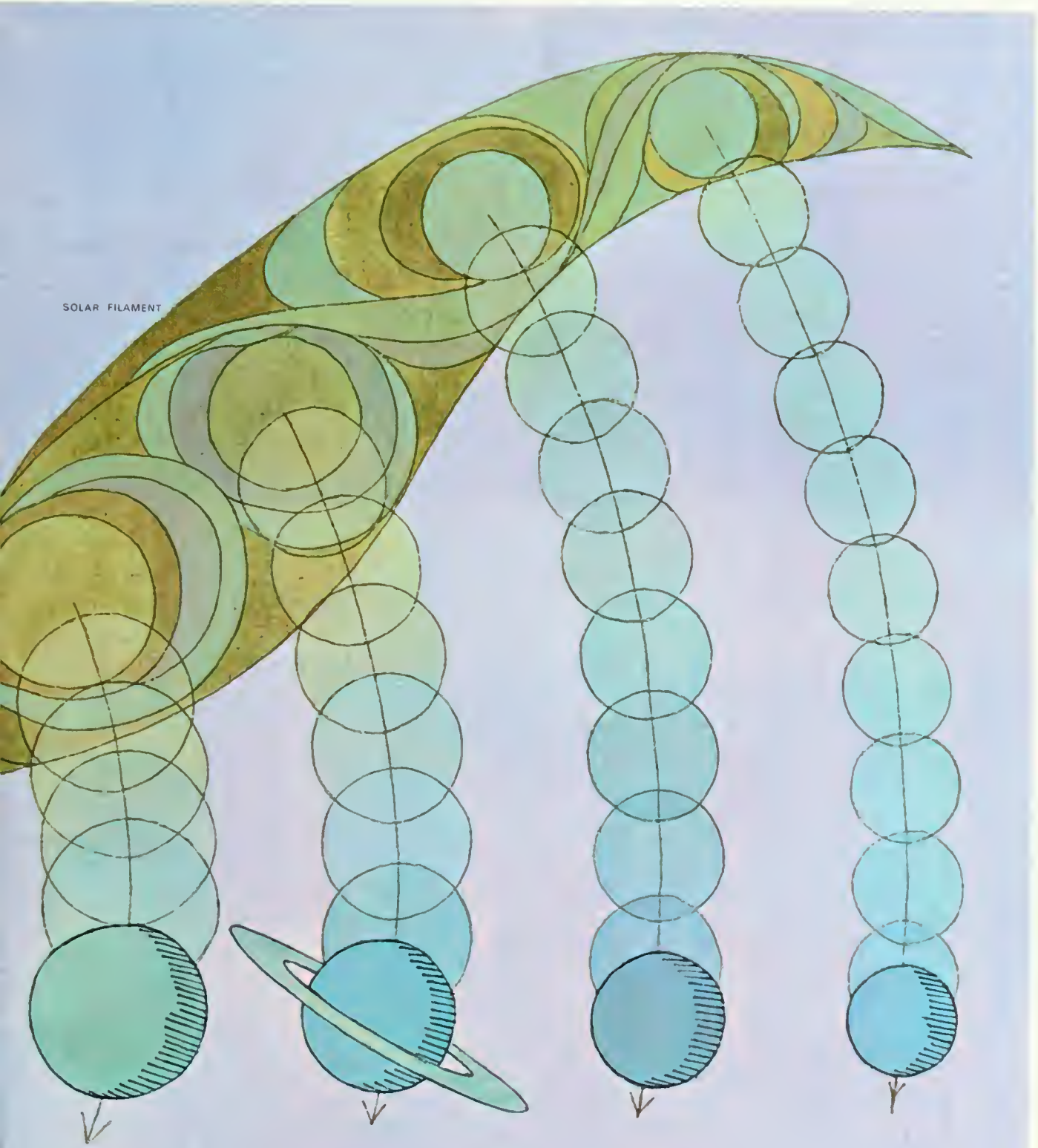
Jeans envisioned the birth of the solar system as a rare event which occurred when the sun was almost sideswiped by a star *(below, left)*. The result of this near-miss was a tidal effect in which a mass of hot solar matter was torn off—the material from which the planets were made.

Jeans's theory seemed sound until, in the 1930s, two flaws were found. Mathematical studies showed that no grazing star could have started the tide moving fast enough to match the revolutionary momentum of the planets. Even if that were possible, the hot solar matter would not have condensed into planets, but probably would have expanded and dispersed.

A SIDESWIPED SUN

In Jeans's hypothesis, a passing star nearly grazes the sun, generating an immense tide in the solar surface. According to Jeans, this surge rose in a huge mountain as the star approached and then "darted out as a long tongue of gas." As the star continued into space, a long filament of solar matter remained, detached from the sun but still within its gravitational field.





THE PLANET-BEARING FILAMENT

The eight planets known in Jeans's day are shown being formed from the long solar filament extending into space, their sizes determined by the varying thickness of the tide. The planets at either end, Mercury and Neptune, are comparatively small while those forming out of the center, Jupiter and Saturn bulk large. Jeans's theory accounted for the sizes of the planets, which are drawn approximately to scale above. A ninth and more distant planet, Pluto, was not discovered until 1930.

An Old Hypothesis Revised

Modern research has added new validity to the old hypothesis that a solar nebula gave birth to the planets. Though the sun now rotates about once every 27 days, recent calculations indicate that the primitive sun must have spun much faster to throw off the material that became planets. But what could have slowed it down?

A group of astronomers, including Britain's Fred Hoyle and Sweden's Hannes Alfvén, provided an answer in the 1950s—that the rotational momentum of the sun was transferred by magnetic lines of force to a disk of gaseous material the sun left behind *(below)*. So efficiently was this done that today the sun accounts for only

2 per cent of the momentum of rotation and revolution of bodies in the solar system; planets have the rest.

Because most stars—distant suns—are rotating slowly like our sun, it is possible that they too have been slowed by a similar process of planet formation. If so, the universe may be dotted with worlds like our own.

SLOWING DOWN THE SUN

The still-forming, rapidly rotating sun spins with its disk of gas in this conception of the Hoyle-Alfvén hypothesis. Magnetic lines of force emerge from the sun, enter the disk and convey the sun's spin to it. As long as the sun turns faster than the disk, these force lines will twist backward until, like springs, they will slow down the sun while forcing the disk outward. Thus most of the sun's rotational momentum passes to the disk—and the planets

2
The Most Familiar Planet

The earth from 35,000 feet, this view of the Carolinas shows the atmosphere's bluish tint.

A CONVENIENT STARTING POINT for investigating the planets is the earth, the planet that can be studied with the greatest ease. Astronomers cannot sample the surface materials or the atmospheres of other planets as readily as they can the earth's, or record vibrations that pass through their deep interiors. They can only look, not touch, depending wholly on data carried across space by light and radio waves—and such information is often vague and baffling.

An effective strategy for interpreting data about distant planets is to assume that the planets are fundamentally similar to the earth, differing chiefly in ways that can be accounted for by planetary evolution. Astronomers believe that the earth was formed at the same time as the other planets and out of similar materials. The same star—the sun—bombarded them all with the same kinds of radiation for about 4.5 billion years, and the same laws of physics and chemistry governed the development of all. They are bound to have features in common, and when these are identified, whole blocks of information amassed about the earth can be transferred, with caution, to other planets.

So a key to the planets is knowledge of the earth, including its earliest history. Without this guiding example the shreds of knowledge that astronomers gather so painfully with their long-distance instruments would be very much more difficult to interpret correctly.

No human eye has yet seen the whole earth as a planet, but indirect evidence tells pretty accurately what it will look like from far out in space. It will be slightly bluish instead of yellowish like Venus or reddish like Mars. The globe will be wrapped in a light-blue haze caused by the preferential scattering of the blue component of sunlight by the atmosphere. This is the same effect that makes the earth's sky look blue. It will not be as bright as Venus because of its lower reflectivity and greater remoteness from the sun, and its surface markings will not be as distinct as those of Mars.

The surface will be partially obscured by brilliant white clouds, some of them large continuous swirls and sheets, others made of smaller patches blended together by distance. Through the haze and gaps in the cloud cover the continents and oceans will show dimly in soft pastel colors, often without sharp boundaries. A large telescope observing the earth from the distance of Venus at its nearest approach (26 million miles) could, with difficulty, detect seasonal changes—snowfalls, cloudless seasons, the springtime growth of vegetation—but they would not be as conspicuous as the seasonal changes on Mars. No works of man would be visible. The observers would get almost no hint of the enormous complexity and variety, both natural and artificial, that the earth's inhabitants know to exist on and near its surface.

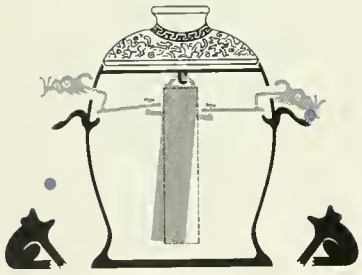
Most of the earth's characteristics that concern man are found in three outside layers that are hardly more than surface films when compared to the earth as a whole. Practically all the atmosphere lies below 100 miles, and the solid rocky crust of the earth is never more than 40 miles thick, usually much thinner. Between them over most of the surface lies

the ocean, which averages less than two miles deep. If the earth were the size of an apple, its crust and atmosphere added together would be about as thick as the apple's skin.

Inside this thin skin lies the bulk of the earth, a hot, not quite solid sphere nearly 8,000 miles in diameter. Its interior has not been seen or sampled, and it has little direct effect on the surface where man lives. But the central mass created the surface layers, which grew on it during its long life like the tarnish that accumulates on an old bronze statue.

Vibrations of the elastic earth

Knowledge of the earth's interior, and by inference its past history, comes mostly from seismology, the science of interpreting earthquake waves. Earthquakes are frequent in the modern earth, most of them caused by movements of the crust that make sudden breaks along "faults," or lines of weakness. When the break occurs, the slightly elastic rock shakes like a broken spring and a long series of vibrations spreads away from the point of breakage. If the vibrations are strong enough they can be detected on the far side of the earth with seismographs, which are instruments consisting essentially of suspended weights whose inertia keeps them motionless while the earth vibrates beneath them. The relative motion between the weight and the ground is amplified by a delicate apparatus and recorded as a zigzag line on a band of paper. By studying this record, seismologists can use the waves as messengers to report what kind of material they have encountered during their journeys through the earth.



A JAR TO LOCATE EARTHQUAKES, this Chinese seismograph of the Second Century A.D. had a pendulum arranged to swing away from the shock wave's source *(opposite page)*. In this diagram, an earthquake has caused the pendulum to swing to the left, forcing open the mouth of one of eight bronze dragon's heads mounted around the jar (only two show in this cross-sectional view). The dragon then drops a ball into the mouth of a bronze toad sitting below. To determine from which direction the shock wave came, an observer looked to see which one of the eight toads had a ball in its mouth. This ancient instrument was probably used only to record earthquakes. Modern seismographs are so sensitive to a variety of waves *(opposite)* that they have become valuable tools for obtaining information on the composition of the earth's inner layers

The waves that plunge deep through the earth are of different kinds. P waves (primary waves) are pressure waves like sound waves in air; they vibrate longitudinally in the direction of their travel. S waves (secondary waves) are like the waves that move along a rope fixed at one end and shaken at the other. Their vibration is across the direction of their travel. Both are made to curve by changes in the physical nature of the material that they pass through, and both are partially reflected by boundaries between different materials. The S waves do not pass through liquids, only through solids, so they serve as a way to find out whether any part of the earth's interior is truly liquid.

Interpretation of seismograms (the records of seismographs) is extremely complicated and gives rise to endless arguments about details, but a general knowledge of the earth's interior, agreed to by nearly all experts, has been extracted from their wiggly lines. The most important single fact is that the earth has a heavy liquid core. It is known to be liquid because the S waves refuse to pass through it. Its density, reported by the P waves, which do pass through it, is right for molten iron under high compression and perhaps alloyed with small amounts of other materials. Any theory about the earth's early history must explain the core, which is 4,300 miles in diameter, bigger than Mars.

A generation ago it was commonly taught that the earth and the planets were torn out of the sun by a star that happened to pass nearby.

This "catastrophic" theory is now out of favor. Most astronomers and geophysicists, both of whom claim the birth of the solar system as part of their jurisdiction, believe that planet formation is a normal process that can happen near any young growing star.

About five billion years ago (says the most favored current theory) a large cloud of dust and gas (mostly hydrogen) floating in space began to concentrate by mutual gravitational attraction somewhere near the center, to form the nucleus of the star that is now called the sun. This body's increase in size made its gravitation stronger and pulled more gas and dust toward it. How long this process took is not known accurately, but eventually the new-formed star got big enough to heat its center to many million degrees and to start thermonuclear reactions somewhat like those that take place in a hydrogen bomb. Nuclear energy released by turning hydrogen into helium made the interior of the new-formed sun hot, the nuclear reactions continued, and it shone stably as a star. It has been shining ever since.

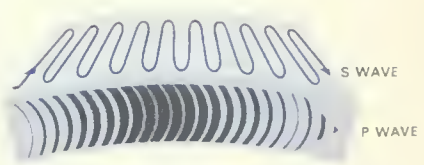
Swirling newborn planets

Astronomers are not sure how the sun's planets managed to condense out of the remnants of the original cloud. The nuclei were small at first and their gravitation was too weak to make objects falling on them hit them very hard. As their mass increased, however, their gravitation grew stronger, and the smaller bodies that they collected hit them with meteor speed, releasing large amounts of impact energy. The bombardment may have heated the young planets to some extent. But for perhaps 500 million years their interiors stayed solid and well under 2,000° F., which is cool by geophysical standards. The next stage of development is not known with any confidence for any planet except the earth, though other planets probably evolved in a related manner.

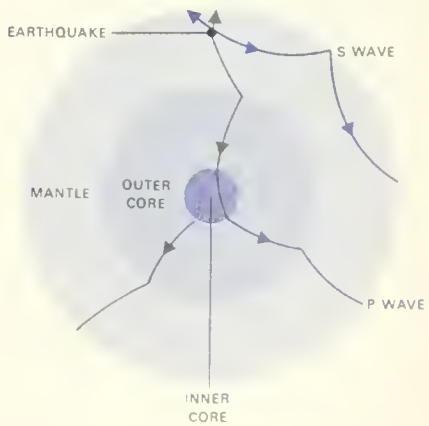
A clue to the earth's condition in its early youth is provided by certain kinds of meteorites, which are believed to be leftover examples of the small bodies that clustered together to form the planets. Since they contain mostly metallic iron and silicate rock, the earth is thought of as having been formed as a coolish globe of iron and silicates, well mixed together.

Along with these main ingredients were small amounts of other elements, some of them radioactive. The most important were uranium, thorium and potassium, which are present today, but there must have also been short-lived radioactive elements that have now decayed to more common nonradioactive elements. As millions of years passed, energy released by radioactive decay gradually heated the earth until some of its constituents melted. The iron melted before most of the silicates, and since it was heavier it tended to sink toward the center, forcing up the silicates that it found there. The earth need not have been largely molten for iron to have migrated to the interior.

At the height of this turnover, the surface must have been a spectacular place. Reflecting the turmoil below as the iron descended, the sur-



TWO KINDS OF SEISMIC WAVES from earthquakes, laterally vibrating S waves and compressional P waves *(above)*, are used by seismologists to study the structure of the earth's inner layers. Some P waves are known to pass through liquids, while S waves merely bounce off them. Thus, when the scientists noted that P waves penetrated the earth's outer core while the S waves did not *(below)*, they concluded the outer core was liquid. Scientists hope to use this method to study the interior of other planets, possibly through "soft-landed" seismological instruments.

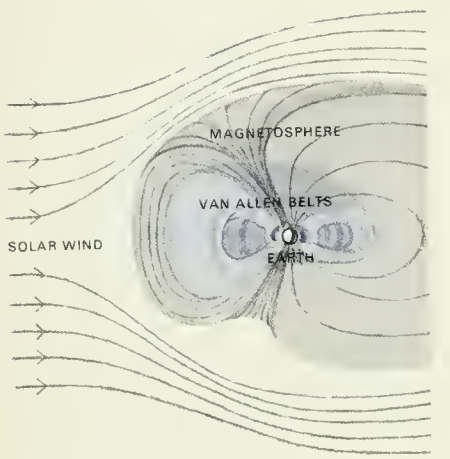


face heaved and bubbled gigantically, with volcanoes exploding through it and lava flowing over large parts of it. At last most of the iron reached the center, where it accumulated as the core. The earth quieted down and formed a thin but fairly stable crust of solid rock.

The earth's interior fires

The earth's metal core is now fairly hot, probably around 7,000° F. Most of it is fluid, but there is evidence that the highly compressed center is solid. The fluid portion is believed to be in circulation, probably caused by heat-induced currents and by the effect of the earth's rotation. This motion is the cause of the earth's magnetic field that makes compass needles point north and south. The details are far from clear, but geophysicists consider magnetism an important clue to a planet's inner character. If a planet possesses a magnetic field, it probably has something like a fluid metallic core. If it lacks a magnetic field, it probably has no core, or a solid, motionless one.

Outside the core is the earth's mantle, which extends almost to the surface and is something between solid and liquid. Like that entertaining substance, Silly Putty, it reacts to sudden motions, such as earthquake waves, like a solid, but flows like a liquid in response to large, long-continued pressures. The mantle is 1,800 miles thick and is made of heavy silicate rock much like the basalt brought to the surface today by volcanic eruptions. Most of the earth's uranium, thorium and potassium are in the outer crust, but the mantle contains some of these radioactive elements, and the heat that they continue to give off contributes to making the earth an active, moderately unstable body.



THE VAN ALLEN BELTS, two bands of charged particles trapped by the earth's magnetic field, were discovered in 1959 by physicist James Van Allen while analyzing radiation data from early Explorer and Pioneer rockets. Explorer XII later indicated that the belts were high-intensity zones of a larger band of radiation called the magnetosphere, extending to about 40,000 miles out from the earth. A similar band of charged particles is known to encircle Jupiter.

Generation of heat in any mass of material is apt to cause movement. The young earth was comparatively cool on the outside because of loss of heat to space. Then, as its interior grew hot through radioactivity, the deep-down material expanded, became lighter and tended to rise toward the surface in convection currents, like hot air rising over a stove. Some geophysicists think a single vertical current started flowing before the core had a chance to form, and passed right through the earth, rising to the surface on one side and sinking down on the other. It forced horizontal currents to flow on the surface itself, and these carried a "scum" of light surface rock toward the place where the vertical current sank down. The scum accumulated there as a great raft of light rock that floated above the general level of the surface. Geophysicists call this raft the "urcontinent" (original continent), and many of them believe that it broke up later into the nuclei of the present continents.

There is much dispute about this, however. All geophysicists now agree that the continents are made of comparatively light rock, mostly granite, and that they float like icebergs in the slightly yielding mantle, but some insist they are of alien origin. Back in its youth, this hypothesis says, the earth was made entirely of heavy rock like the mantle. Then one or more smaller bodies made of lighter rock plunged into it, and their material spread out on the surface to form the high-standing

continents. A body 1,400 miles in diameter would provide enough material for all the continents, while a modern asteroid the size of Ceres (diameter 440 miles) would supply enough for Australia or Antarctica.

There are several objections to this idea. A more widely favored view holds that the continents were created by currents that flowed for billions of years in the mantle, stopping intermittently and starting again. After the core had formed, it blocked any single current that may have been flowing through the earth's center. In place of the single current were several convective cells, or streams of slowly rising and sinking material. One of the currents may have risen under the urcontinent, making it split and moving the fragments apart like pieces of a broken ice floe. This is one explanation of continental drift, a theory originally based on the similarity of the opposite shores of the Atlantic. If North and South America were moved toward Europe-Africa, they would fit together nicely with a little pushing, and the old coal-bearing mountains of North America would neatly join the coal districts of Europe.

Continents that float

The startling idea that the great continents have drifted like logs in a pond was scoffed at for many years, but recently a great deal of evidence has been found to support it. It is known that when certain kinds of rock are formed, either by settling sediment or cooling lava, magnetic particles in them behave like compass needles, lining up with the earth's magnetic field, which for fundamental reasons tends to point north and south. This happened in ancient rocks too, and if they had stayed in the same position since their formation, their magnetism would still point north and south. In some cases it does, but many ancient rocks have been found with fossil magnetism pointing in other directions. This is taken to indicate that they have shifted position since they were formed. Careful study of thousands of such rocks tends to support the theory that the continents have drifted widely.

Apparently the mantle currents are still flowing, and the continents are still adrift. Some of them are splitting up. Mexico's peninsula of Lower California and a part of the U.S. state of California including Los Angeles are moving toward the Aleutian Islands at the rate of two inches per year, breaking away from North America along the line of the famous San Andreas Fault that passes through San Francisco. Another movement is separating Africa from Asia. The Red Sea and the deep rift lakes of East Africa may grow in a few hundred million years into an ocean as wide as the Atlantic.

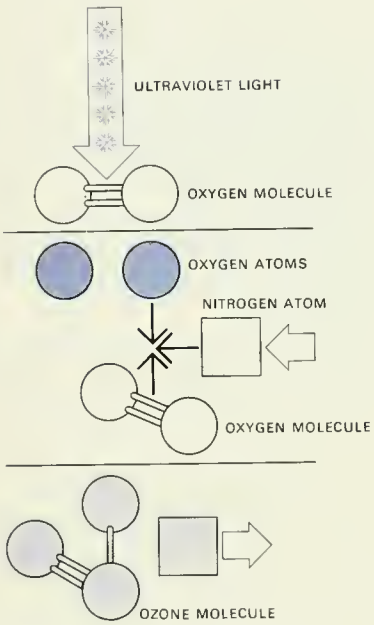
Whether other planets have, or ever had, similar motions in their interiors and crusts is unknown at present. Scientists are eager to find out, and the better they understand the history of the earth's continents and ocean basins the better they can disentangle the evidence that they hope to collect about the other planets.

From the human point of view, the earth's surface, thinly wrapped in water and air, is the most important zone of the planet. So once the ma-

jor features of the crust have been accounted for, the next step is to trace the history of the oceans and atmosphere, which together hold the secrets of the origin of life.

Astronomers who study the sun and stars know that they are made almost entirely of hydrogen and helium. These light gases are extremely scarce on the earth, which is made predominantly of heavy materials. Something must have happened to separate the cosmically rare heavy elements from the hydrogen and helium that made up most of the cloud out of which the sun and its planets were formed. The most successful theories hold that the sun drove the light gases away.

It is a basic physical principle that when gases are mixed together at any uniform temperature, most of their atoms (or molecules) are moving rapidly, and the higher the temperature the faster their average speed. The light ones also move faster than heavier ones. Hydrogen, the lightest, moves fastest of all, followed by helium, the second lightest. When the earth was being formed, any hydrogen or helium atoms near it were made to move so fast by solar radiation that they escaped from the earth's gravitation just as if they were rockets exceeding the modern earth's escape velocity. Heavier gases went with them, perhaps during a brief period in the sun's youth when it was much more luminous than it is now.



THE FORMATION OF OZONE from molecules of oxygen in the upper atmosphere *(diagramed above)* is part of a cyclic series of chemical reactions that prevents lethal rays of ultraviolet light from reaching the earth. The process starts when ultraviolet light *(arrow)*, streaming down from the sun, hits an oxygen molecule and breaks its atoms apart. The impact adds momentum to the unhitched oxygen atoms and one of them undergoes a three-way collision *(middle)* with another oxygen molecule and a molecule such as nitrogen *(square)*. The result is a molecule of ozone. Eventually the ozone will absorb an ultraviolet ray and break down into oxygen to start the cycle again. It is this last process that shields life on earth from the most lethal rays.

An earth devoid of atmosphere

Their departure left the earth almost bare of gases, so its present atmosphere must have come out of the interior, accumulating slowly as the ages passed. This idea is easier to accept when it is remembered that the atmosphere, which seems large to dwellers on the earth's surface, is less than one millionth of the planet's total mass. The oceans are about one four-thousandth of the total, and so a modest amount of outgassing—escape of volatile constituents from the interior—can easily account for both of them many times over.

The outgassing still continues, though probably not as strongly as before. Besides the gases that roar so conspicuously out of volcanoes, a probably larger contribution comes from volatile matter that escapes from steam vents or seeps quietly through the floor of the ocean. It has been calculated that modern hot springs contribute enough "juvenile" water (water that has never been to the surface before) to replace the entire ocean in about three billion years.

It is very likely that the young earth's first outgassed atmosphere was very different from its present one. Still reflecting the cosmic abundance of the elements, it was composed predominantly of hydrogen and hydrogen-rich gases. In such a "reducing" atmosphere no free oxygen can form. Besides inert nitrogen, it contained methane, the principal component of natural gas, ammonia, water vapor and perhaps a small amount of carbon dioxide.

The water vapor in it was vulnerable to destruction by ultraviolet light coming from the sun. At present these powerful rays are absorbed

by oxygen at high altitudes where there is little or no water, but in the early years, when oxygen was lacking, the ultraviolet light could reach water molecules and split them into hydrogen and oxygen. Most of the hydrogen quickly escaped into space while the oxygen reacted with methane or ammonia, forming principally carbon dioxide, nitrogen and water, or was absorbed by oxygen-hungry materials in the earth's crust.

This process of splitting water molecules, which is called photodissociation, may have been slow, but it gradually removed by oxidation part of the methane and other reducing gases in the atmosphere. Specialists in the early history of the earth do not agree as to whether it yielded any permanent free oxygen, but it certainly made it easier for oxygen to accumulate by eliminating some of the gases which react with oxygen. And about four billion years ago, perhaps earlier, a much more remarkable process was beginning: the first feeble start of life, which would eventually control the composition of the atmosphere.

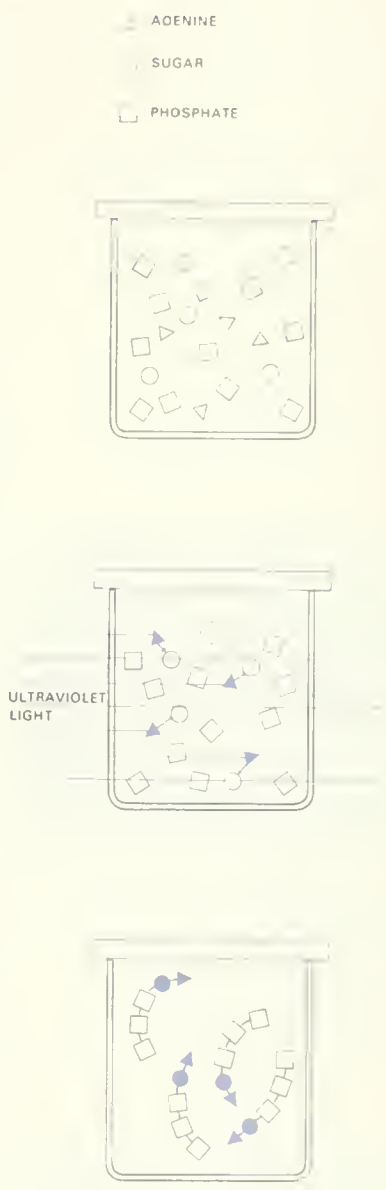
It is not easy to imagine the earth four billion years ago. Perhaps it had oceans covering much of its surface, perhaps only separate seas in low places. There was no life, not even bacteria. In that strange unbreathable atmosphere, the sky must have been blue; presumably it had clouds, and rain fell from them, for traces of water erosion are found in rocks formed considerably earlier.

The sunlight reaching the surface then contained ultraviolet rays that would kill most modern creatures, but this same ultraviolet also had the apparently paradoxical effect of helping the start of life. When its powerful ultraviolet rays broke up simple molecules in the atmosphere, some of the fragments united to form organic compounds such as aldehydes and cyanides. These, being heavier than most atmospheric constituents, sank to the surface or were washed down by rain.

The ancient soupy oceans

Gradually the new compounds accumulated in the growing oceans. As millions of years passed and these compounds interacted, the ocean water became a solution of organic matter whose molecules joined together under the stimulus of ultraviolet light, growing bigger and more complicated. Some of them were compounds that play key parts in the chemistry of life on the earth today. They could not possibly survive in the modern ocean, where they would be snapped up as food by microorganisms, but in the ancient ocean there was nothing alive to eat them so they survived and accumulated. The ocean may have grown as rich in organic material as consommé.

This is not mere guesswork or scientific romancing. The first steps of the process can be duplicated in the laboratory by putting methane, ammonia, water and hydrogen in a sealed glass container to simulate the ancient atmosphere, and passing electric sparks through them to play the part of the energy that was added by ultraviolet light or lightning. The product is a rich organic mixture including amino acids, the building blocks of the proteins. More elaborate experiments, some of



THE FUEL OF EARTHLY LIFE, adenosine triphosphate (ATP), may have been created from simple substances floating in a primeval sea. These drawings indicate how ancient ultraviolet radiation acting on three such substances — adenine, sugar and phosphate — could cause them to unite in energy-charged molecules of ATP *(bottom)*. Ultraviolet activity on other planets may have formed similar organic molecules, and perhaps even life itself

which used ultraviolet light, have proved that many other substances of biological importance can be synthesized out of simple compounds by the natural action of physical and chemical laws in primitive planetary environments. The long list includes ATP (adenosine triphosphate), which stores energy in vital life processes, and the nucleotides, the building blocks of nucleic acids, the basic hereditary materials.

Oceans of evolving creatures

If such feats of creation are possible in the laboratory, it is not much strain on credulity to believe that an ocean of organic solution illuminated by ultraviolet for a billion years might produce a great variety of molecules, including very complex ones that would have some of the attributes of living organisms, gathering material from their surroundings, using it for growth and storing sufficient information to make accurate replicas of themselves. If such molecules have, in addition, the ability to evolve and become more efficient, they can be considered truly alive.

This is what is believed to have happened about four billion years ago. The organisms that came into existence then were certainly very much simpler than the humblest modern bacteria or viruses, perhaps even simpler than the large molecules of nucleic acid that control the reproduction of all modern living things. These organisms probably lived sluggishly, taking a long time to multiply. For a while there may have been several or many kinds with different chemistry. If the earth had separate seas with no connections between them for long periods, which is quite possible, each sea may have developed its own types of life.

But true Darwinian evolution was at work at the molecular level. By accidental changes (mutation), a few of the organisms became more efficient and passed their advantages to their descendants. They multiplied faster, and starved their weaker rivals by competition for food in the soupy water. At last came a turning point when a single organism blessed by a favorable evolutionary change became so much more efficient than the others that its swarming progeny spread through the waters of the primitive earth, exterminating all competitors. There is little doubt that this great event actually happened. The proof is that every organism alive on earth today, from bacterium to man, has the same complicated basic chemistry. So all must be descendants of that single triumphant, submicroscopic speck that conquered the oceans billions of years ago.

For a long time, perhaps several hundred million years, the primitive organisms remained small, inefficient and not nearly so numerous as the creatures that swarm in the modern ocean. Their only food was the ocean's sparse and probably dwindling supply of organic material, created by ultraviolet light. But they were evolving and improving. Eventually some of them developed the ability to absorb ordinary visible light and use its energy to make food materials out of water and carbon dioxide.

This process, photosynthesis, gave great new impetus to life on earth. No longer need life depend on a chance trickle of food. The new photosynthetic organisms—plants—could make their own food, limited only

by the bounty of readily available sunlight. Animals promptly evolved to eat the plants and multiply along with them.

Green-plant photosynthesis meant the end of the earth's early atmosphere. When the newly evolved plants used carbon dioxide and water to make sugars and other foods, the reaction dissociated the water to release large quantities of free oxygen. The process was probably slow at first, starting in shallow, sunlit pools where photosynthesis was especially active. Later the oxygen spread throughout the oceans and air. Eventually it eliminated almost all methane, ammonia and other reducing compounds, and then began to accumulate in the atmosphere.

The great life cycle

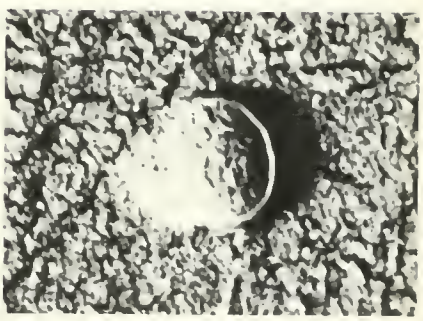
The earth's modern atmosphere has about 20 per cent oxygen, and there is no doubt about where it came from. The photosynthesis of existing plants on land and in the oceans is vigorous enough to supply all of it in 2,000 years, a mere tick of the clock on the geologic time scale. Animals large and small eat the plants, take in oxygen by breathing, and exhale carbon dioxide, which is reabsorbed by the plants, thus completing the carbon cycle that is the mainspring of life. At present the plants are far ahead. The atmosphere and the ocean contain only a trace of carbon dioxide. The plants absorb it as fast as the animals that have eaten their fellow plants put it back in circulation.

The modern atmosphere is dominated by the plants, and its richness in oxygen makes it unique among the planets. Apparently the earthly type of photosynthesis is not in operation anywhere else in the solar system. This does not mean in itself that life does not exist on other planets. If the earth's atmosphere had been examined before photosynthesis won its victory billions of years ago, it would have shown no more than a trace of free oxygen, but nevertheless life was in full development in the oceans. Other planets may have kinds of life that do not release oxygen.

Though astronomers know they will not find earthlike conditions anywhere, they minutely study the earth's atmosphere as a key to the characteristics of other atmospheres which will have controlling effects on the surfaces and climates of their planets. But understanding the earth's atmosphere is not easy. It looks simple enough when examined from the ground with uninstructed eyes, but actually it is a many-layered thing, in constant complicated motion.

In a sense the ocean is part of the atmosphere, since it is made of easily volatile material and owes its liquid state to a delicate balance of temperature. It can also be considered part of the earth's crust because part of it is frozen solid in glaciers and ice caps, which were bigger during at least two major periods of geologic history.

They may get bigger again or they may disappear, and the size of oceans may fluctuate. If the temperature of the earth's surface should rise by only a few degrees, part of the liquid water would join the atmosphere as water vapor. A sufficient increase would dry it up entirely, giv-



A CLUE TO PLANETARY LIFE may be offered by these fossils, discovered in ancient rock by Harvard scientists. The primitive fossil above, the oldest yet found, dates back 3.1 billion years and yet its double-layered cell wall is characteristic of modern bacteria. The more visible fossil below is a rod-shaped bacterium that lived about two billion years ago. Life on other planets may have evolved—or may now exist—in similar rudimentary form.

ing the earth an atmosphere predominantly of steam. Because of the greater pressure of the steam-filled atmosphere, the temperature required to evaporate the ocean would have to be considerably higher than the present boiling point of water. Geophysicists do not expect this temperature to be reached, at least for a very long time, but they agree that the extensive film of liquid water on most of the earth's surface is an unusual borderline phenomenon not likely to be found on other planets in our solar system.

The atmosphere's lowest gaseous layer, the troposphere extending to about 35,000 feet, is the familiar air that living creatures breathe and through which most airplanes fly. When clouds are absent, nearly all the visible light in sunlight passes through the troposphere to the ground and raises its temperature. The ground tries to give this energy back to space by its own radiation, but its comparatively low temperature permits it to radiate only infrared light whose wavelength is very much longer than most of the radiation emitted by the sun. Like the glass of a greenhouse, the troposphere is not transparent to infrared radiation of such a long wavelength. The small amounts of water vapor and carbon dioxide that it contains absorb infrared light and use it to heat the air at low levels. This "greenhouse effect" is one of the reasons why the air is warmer near the earth than it is higher up.

Heat engine at the equator

Another reason is that the ground heats the base of the troposphere by contact. This kind of heating is strongest near the equator, so the troposphere gets hottest there. The air rises, flows toward the Poles and is replaced by cooler air moving horizontally from temperate latitudes. This equatorial "heat engine" is the primary cause of the intricately swirling winds that meteorologists must disentangle to understand the weather. Winds are probably blowing on other planets, produced by the same or similar heating effects.

The top of the troposphere is called the tropopause, and above it is a relatively motionless zone, the mesosphere. Convection currents rarely rise into it, so it gets little heat from below and contains little water vapor. Its most important constituent is a small amount of ozone, an active form of oxygen whose molecules (O_3) are made out of ordinary oxygen (O_2) that has been broken up by ultraviolet light. Ozone is violently poisonous, so it is just as well that it stays in the mesosphere, but it also has a beneficial effect on the earth's life. It strongly absorbs a kind of ultraviolet radiation that would kill all the earth's contemporary organisms, if unprotected, by destroying the vital nucleic acid in their cells.

There is only a trace of ozone in the whole atmosphere. The total amount is equivalent to a layer one one-hundredth of an inch thick at surface pressure, but without it all life on earth would have to stay out of the light, or die. If other planets lack an ozone or an equivalent atmospheric screen, any life that has developed upon them must have found some different protection against the deadly rays contained in sunlight.

Above the ozone layer are other levels of the atmosphere that absorb ultraviolet light, and some of them are ionized, containing large numbers of free electrons knocked off their atoms by energy from the sun. These layers reflect certain kinds of radio waves, guiding them around the earth and so permitting them to be used in long-distance communication.

The never-returning atoms

The outermost zone of the atmosphere is the exosphere, starting at 300 miles. The air at this altitude is so thin that its atoms seldom collide with one another, as they do hundreds of millions of times per second at surface density. Instead they follow ballistic courses like artillery shells, curving high and then down again. Some are on orbits around the earth and are true satellites. The fastest of all, those that have received extra-powerful boosts from violent collisions with other atoms, achieve escape velocity. They soar out of the atmosphere into space and never return to the earth. Most of the defectors are hydrogen atoms separated from water molecules by photodissociation. They are not numerous. About one pound of hydrogen escapes from the earth per second, which is not a significant amount on the geologic time scale, and the loss is partly made up by protons, the nuclei of hydrogen atoms, arriving from the sun.

The exosphere frays out gradually, with more and more of its atoms on their way toward permanent escape. Above the base of the exosphere lie the Van Allen radiation belts, the streams of spiraling protons and electrons which have come from the sun and have been trapped by the earth's magnetism. They were discovered by early U.S. satellites and are considered serious hazards for manned space flight at certain altitudes. These belts and the earth's magnetic field extend to about 40,000 miles from the earth; there, the charged particles from the sun overwhelm the feeble magnetism of the distant earth. This is the magnetopause, the final frontier between the earth and interplanetary space.

When astronomers study the distant planets, they search eagerly for the slightest clue that suggests a feature of the well-observed earth. The presence of carbon dioxide in a planet's atmosphere indicates that the greenhouse effect is heating the surface below. The presence of ammonia or other reducing gases shows that the planet is in something like the earth's early condition before the development of green, photosynthetic plants. A planet's surface markings, if any are visible, are compared with the earth's in hope that the forces that drew them can be understood by analogy with the influences understood on earth.

It is known already that the earth is unique in one respect: no other planet has anything to compare with its rich production of radio waves. If the earth were observed with modest radio telescopes from Mars or Venus, it would show as a powerful radio source, more brilliant at certain wavelengths than anything else in the sky. This radio flux is of biological origin. It is the ceaseless uproar of man's TV and radio broadcasts, escaping into space through the ionized layers of the upper atmosphere.

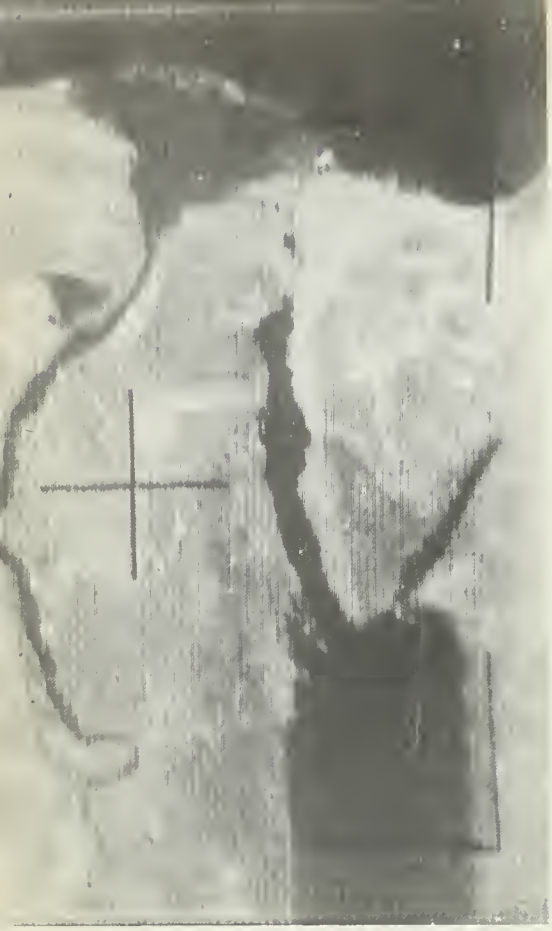
A Space Visitor's View of the Earth

Of the nine planets in the solar system, our own earth is the only one that has been even superficially explored by man. At that, although he has roamed his home planet for a million years, man's firsthand knowledge is limited to a narrow belt extending a few miles above and below the surface. No human eyes have ever seen the earth as it might look from Mars *(opposite)* or have perceived the nickel-iron mass that is believed to make up the earth's core—and which accounts for more than one eighth of the planet's volume.

Yet what *is* known about the earth can often be cautiously applied to its companions, all of which are assumed to have been similarly born as solidified clouds of dust and gases left over from the creation of the sun. Although no two planets are identical, man can learn important fundamentals about all of them—and perhaps avoid serious mistakes—by studying his handy planet as though it were a foreign body. For the information today's scientists glean about the nature of the earth's atmosphere, structure and forms of life will provide clues to what tomorrow's interplanetary explorers can expect when they venture into the universe.

THE EARTH FROM MARS

The earth, shown as it might look through a telescope from Mars, more than 35 million miles away, appears as a blurry, bluish globe that grows larger and more shadowed as it approaches on its shorter orbit and passes between Mars and the sun. The earth's clouds obscure some features, but the oceans can be distinguished, as can large land masses like South America *(lower left)*.



THE EARTH FROM 400 MILES

These photographs, taken by orbiting weather satellites, show the earth as light areas of land near a darker surface. Although the land details are indistinct, the outlines traced by the contrasting areas are very distinct. The Mediterranean Sea, Red Sea and Nile River are all easily identifiable in the cloudless view of Egypt *(left)*. The Eastern Seaboard of the United States is clearly visible, below, from Maine *(upper right)* to Delaware Bay *(lower left)*, while the British Isles *(right)* can be seen in their entirety

A World of Land and Water

The difficulty of detecting even intelligent life on some other planet is illustrated by these pictures of the earth taken from about 400 miles. Although familiar geography emerges clearly—the Nile River in the view of Egypt *(opposite, top)*, the mouth of the Hudson River in the photo of the United States' Eastern Seaboard *(opposite, bottom)*, and the English Channel in the picture of the British Isles *(left)*—the three great cities that should be seen in these pictures (Cairo, New York and London) are invisible, as are bridges, railroads and other man-made works.

While it is impossible to determine the presence of life from pictures like these—similar photographs of Mars were taken from 8,160 miles away during Mariner IV's 1965 flyby—the contrast between dark and bright areas implies different surfaces. One of them could be water, which seems essential to the formation of earth-like life, though not necessarily to other kinds that may exist elsewhere.

Signs of Life from 150 Miles Up

It probably will not be necessary for a space explorer actually to set foot on a planet to determine if anything like a human society exists there. He might be able to prove this with a hand-held camera from 150 miles if his view was not obscured by clouds. From this elevation, he could see panoramas as detailed as these on the earth, in which bridges, roads, farms, even rocket launching pads, are clearly visible. Unnatural straight lines and geometric patterns, like those at Cape Kennedy *(left)*, would instantly indicate the presence of an advanced civilization.

A man gazing down through the earth's blue haze—caused by the atmosphere reflecting back the blue component of sunlight—at Southern California's Imperial Valley *(right)* can distinguish not only man-made squares, but also evidence of folding in the rock structure of the mountains.

A LONG LOOK AT CAPE KENNEDY
This picture of the 100-mile-long Canaveral Peninsula, its Cape Kennedy launching pads visible at the upper right, was taken in 1965 from Gemini V, orbiting 150 miles above the earth. The white puffs are an earth phenomenon: cumulus clouds which form only over land.

HIGH ABOVE A DESERT VALLEY
California's Imperial Valley and Salton Sea, as seen from Gemini V (partially visible at lower left), lie in a basinlike depression created by ancient earth faults. Most of the squares at right are cotton and alfalfa farms, while in the far background the state of Arizona is visible.

An Ice City That Never Was

If men judged planets by their first appearances, they would be just as wrong as Christopher Columbus was when he landed in the Antilles and thought he was in the Orient.

The picture above, an earthly version of a scene like one that might be transmitted by a "soft-landed" planet exploratory vehicle, is open to two misinterpretations. The first, which no trained scientist would make, is to translate the shapes in the background into the skyline of a city like San Francisco *(right)*. The second, and more reasonable error, is to assume that such a bleak and desolate vista is typical of an entire planet. But just as the earth can produce ice packs and jungles within a relatively limited temperature range, so other planets can be expected to present equally contrasting terrains. Astronomers have already observed what appear to be polar ice caps on Mars, which may actually turn out to be just a thin frosting of ice crystals.

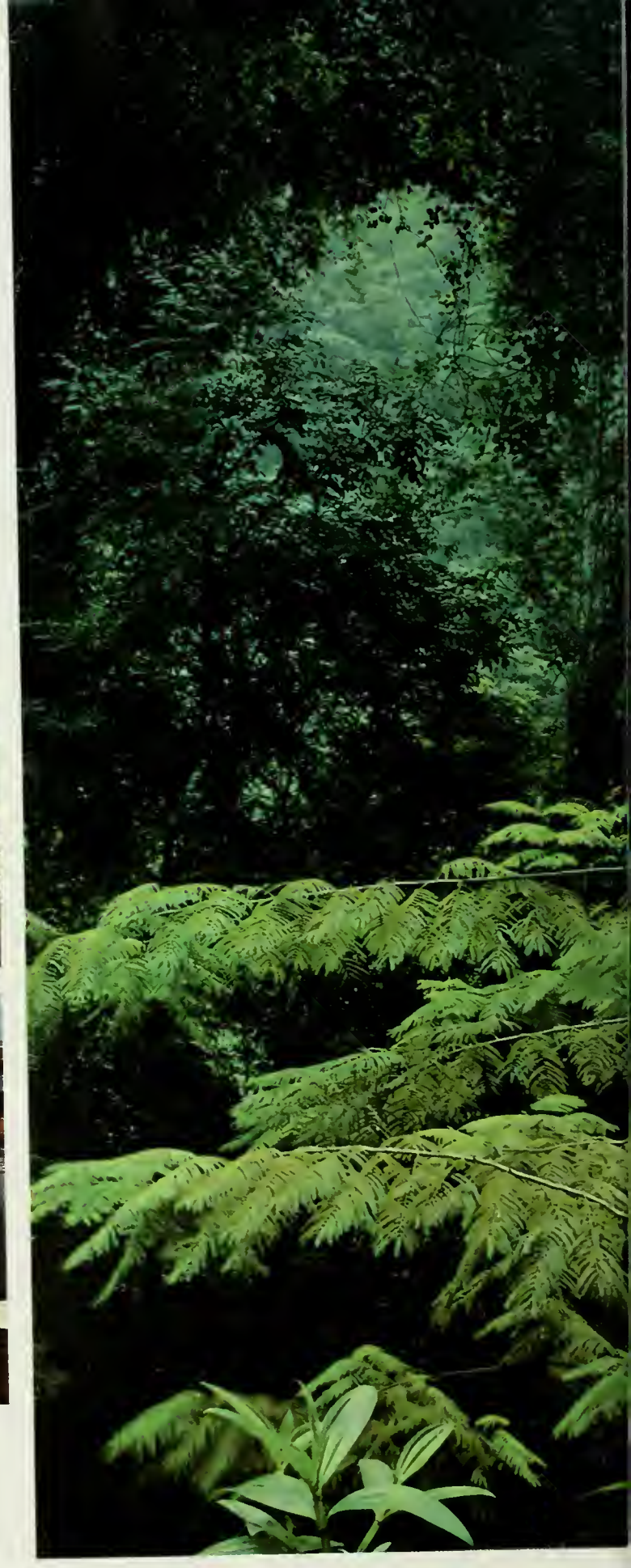
THROUGH A VISITOR'S EYES

The deserted Antarctic panorama above would probably puzzle a visitor from another planet. He might not recognize either the water or the ice for what they really are. At a brief glance —such as might be obtained by "soft landed" cameras—he might very easily equate the similar patterns of breaking-up ice in the distance and hillside homes in San Francisco *(left)*, and conclude that he was seeing the same phenomenon. He might become even more confused if he noticed the single visible clue to life that appears amid the expanse of frozen desolation —the set of penguin tracks in the foreground.

The Seasons of a Tilted World

What an interplanetary visitor to the earth—or any other heavenly body—saw around him might depend not only on where he landed but on when he landed there. The earth's face alters radically from season to season.

Seasons result from a fixed tilt in the earth's axis, which turns the Poles alternately toward the sun. Above the Arctic Circle, frozen tundra *(bottom)* flowers in July, when the sun shines 24 hours daily. In the winterless equatorial zone, jungles and rain forests *(right)* flourish. Between the extremes are the temperate zones, where the changing beauty of trees *(far right)* reflects the seasons.



A SUDDEN SUMMER
The treeless tundra of the Canadian Arctic, some 1,000 miles below the North Pole, comes alive briefly but spectacularly in the summer. Because of the earth's tilt, the sun then shines almost constantly, thawing the frozen ground and giving life to some 900 species of flowers.

TREES FOR ALL SEASONS

The junglelike rain forest of Brazil *(left)*, a product of a hot climate and tropical trade winds, probably could not survive a freeze and may never have to. In temperate zones, however, trees react to seasonal temperature changes. In the pictures above, the flowering apple tree of an Austrian spring, the silvery birches of a French autumn and the snowy pines of an American winter all share this adaptability. A series of regular but unexplainable brightness changes on Mars has been interpreted as a sign of the changing seasons on that planet.

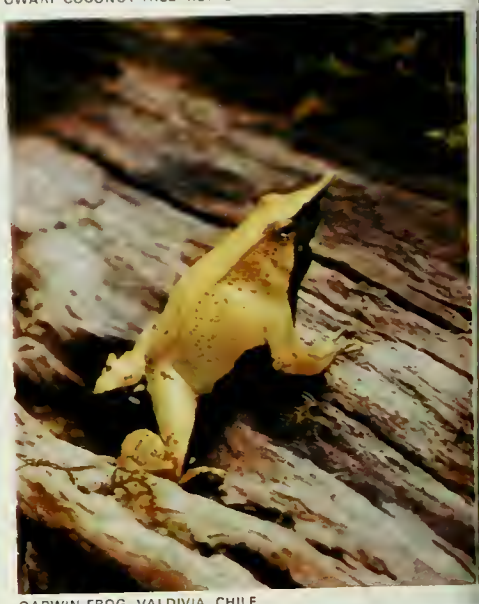
The Many Faces of Life on Earth

Some scientists think that 100 billion planets capable of supporting life exist in the Milky Way. But the impossibility of predicting what forms such life might take is demonstrated by the variety and unpredictability of life on earth. More than four billion years of evolution have produced several million distinct types of living flora and fauna within the earth's atmosphere. These range from microscopic bacteria to 100-foot whales, from man himself to the Australian platypus, an evolutional oddity which is an egg-laying mammal possessing the bill and webbed feet of a duck and the tail of a beaver. As on earth, life on other planets may differ every few miles. The Darwin frog, for example, is found in a single forest of Chile and nowhere else, although the earth contains many similar forests.

BASKET GRASS TEXAS

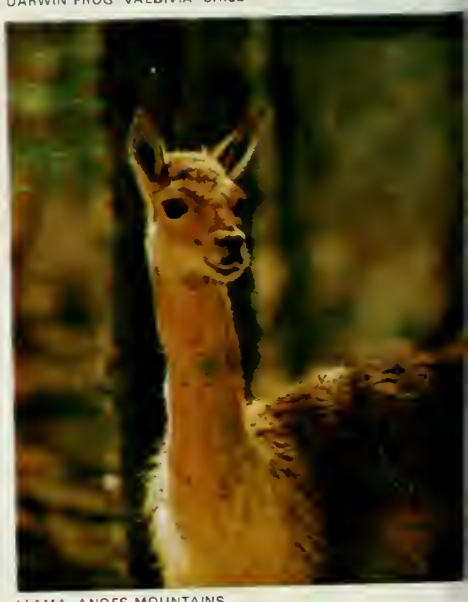
DWARF COCONUT TREE KOH SAMUI ISLAND

TIGER ASIA



DARWIN FROG VALDIVIA CHILE

GREEN PYTHON NEW GUINEA



LLAMA ANDES MOUNTAINS

THE RESULTS OF EVOLUTION

Each living earth creature shown here has something in common with the others: the basic chemistry of its life processes. Except for the nematodes, worms that float in all of the earth's oceans, all of these creatures are found only in the limited areas indicated—a sign that a wide variety of life is possible and that completely different types may exist on other planets.

GOOSE BARNACLES CALIFORNIA AND OREGON

ELEPHANT'S EAR JAVA

MILKWEED EASTERN UNITED STATES

NEMATODES ALL OCEANS

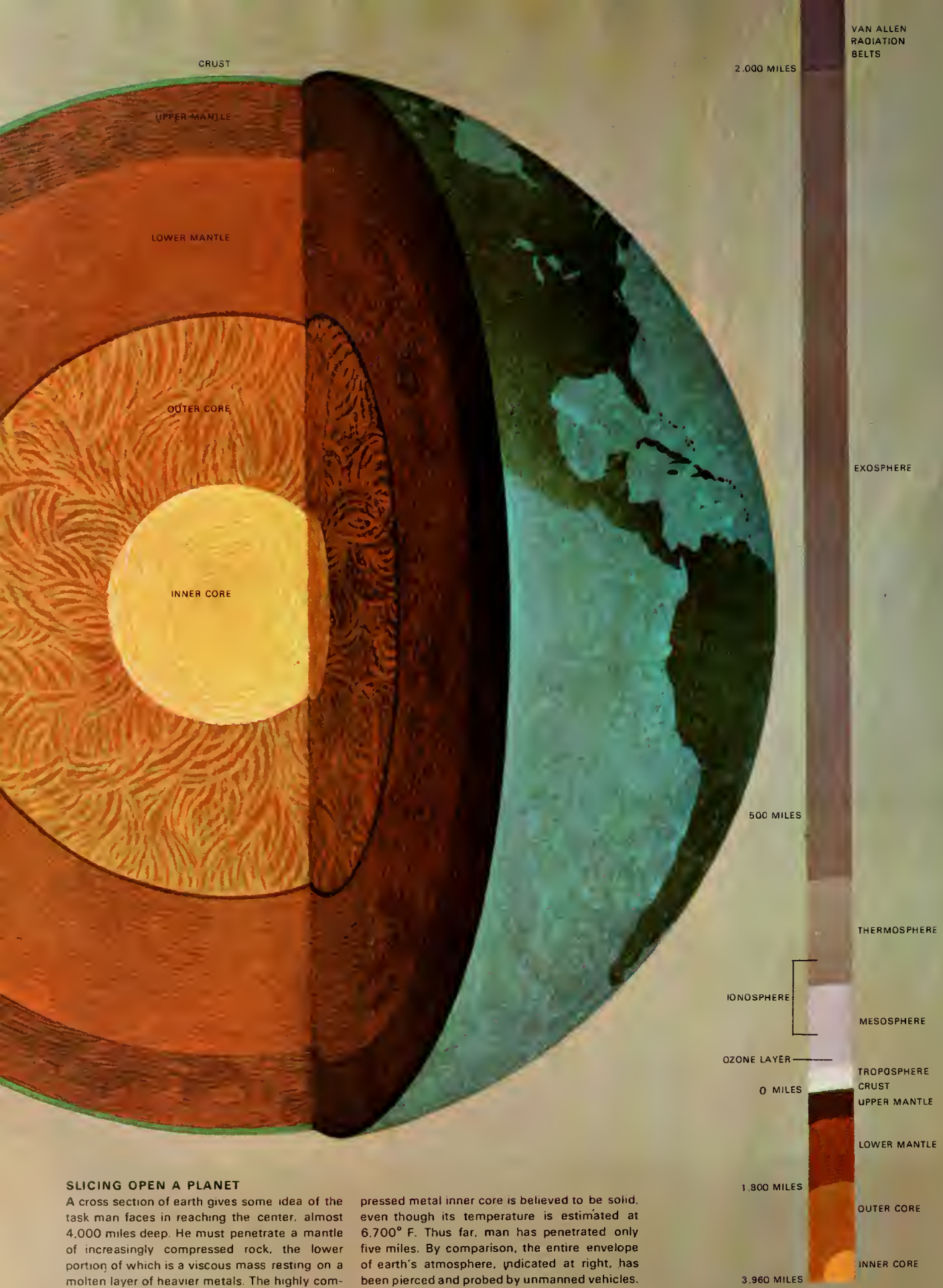
GRAMA WEST INDIAN WATERS

TENREC MADAGASCAR

SILK SPIDER THAILAND

WHITE-LIPPED GARDEN SNAIL EASTERN UNITED STATES

CASSOWARY NORTHERN AUSTRALIA



SLICING OPEN A PLANET

A cross section of earth gives some idea of the task man faces in reaching the center, almost 4,000 miles deep. He must penetrate a mantle of increasingly compressed rock, the lower portion of which is a viscous mass resting on a molten layer of heavier metals. The highly compressed metal inner core is believed to be solid, even though its temperature is estimated at 6,700° F. Thus far, man has penetrated only five miles. By comparison, the entire envelope of earth's atmosphere, indicated at right, has been pierced and probed by unmanned vehicles.

The Skies Above, the Earth Below

To help man in forming meaningful conclusions about the composition of other planets, he must fully explore the last two frontiers of the earth—straight up and straight down.

The rockets, balloons and satellites of space technology have unlocked many mysteries of the atmosphere. As the indicator opposite shows, the road to space—and to interplanetary travel—is well charted. Above the familiar region of breathable air—the troposphere—lies the mesosphere, whose lowest layer contains a screen of ozone molecules which filter out the sun's ultraviolet rays. Extending from the mesosphere into the adjacent thermosphere is the ionosphere, with its flickering auroras and luminous clouds. The exosphere begins about 300 miles up and extends to include the Van Allen belts—a huge region of charged particles that are trapped by the magnetic attraction of the earth.

Far less is known about the composition of the earth itself. In 1909 Andrija Mohorovičić found an abrupt velocity change in seismic waves, indicating a clear division between the earth's rocky crust and its heavier underlying mantle. But man has yet to penetrate physically the Mohorovičić discontinuity—better known as the Moho. It is mostly through study of earthquake waves, as well as of subsurface heat-flow measurements and magnetic surveys, that scientists have constructed the cross section opposite: a metallic inner core with a radius of about 800 miles surrounded by a molten outer core 1,300 miles thick and a crystalline mantle about 1,800 miles thick. Compared to these, the earth's crust, only five to 25 miles deep, is a very thin skin. And the highest and lowest spots on earth —Mount Everest and the Marianas Trench *(below)*—are mere wrinkles.

WRINKLES ON THE EARTH

The earth's crust shifts constantly, possibly because of the slow movement of the mantle beneath. The surface extremities—five-mile-high Mount Everest and the seven-mile-deep Marianas Trench in the Pacific Ocean—are thought to be wrinkles, not breaks, in the relatively light crust. The crust's outer layer, which consists of granite on land and sediment under the seas, is lined with harder basalt. Although volcanoes are natural breachings of the Moho separating the crust from the mantle, man's deepest drilled penetration has not yet pierced the earth's crust.

A Constantly Changing Planet

Ever since its birth in a cloud of spinning stardust about five billion years ago, the earth has been changing. There are tremendous forces at work deep within its structure, powerful enough to rip open the earth's crust and to move continents about like drifting icebergs. Not until man arrives at a clear understanding of these forces will he decipher the last of the riddle of how the earth—and its sister planets—evolved.

Until then, scientists can only theorize. One theory is that the earth originally contained a single land mass that began breaking up three billion years ago *(opposite, top)* into two continents, which some scientists call Laurasia and Gondwanaland. These in turn broke up into the shapes we know *(center)*. The slow movement of the earth's inner structure *(below)*, which is supposed to have set the land masses adrift, is still operating. In 10 million years the world may resemble the map at the bottom of the opposite page—with California drifting out to sea, Florida linked to South America, and Africa moving away from Asia and Europe.

THE DRIFTING CONTINENTS

The shifting of land masses of the earth—evidenced, for example, by the slippage of California coastlands into the Pacific at a rate of two inches per year—intrigues and baffles scientists. A theory that has received new support in recent years was first expounded by Vening Meinesz in the 1920s. Diagramed above, it assumes a convectional flow of hot material within the mantle. The ascending flow forces the crust apart, creating volcanoes and undersea ridges. The descending flow pulls the crust downward, forming deep faults and trenches and compressing adjoining land into mountainous masses, which then slowly drift into the openings. These forces, still at work, could one day produce a strange new world *(opposite)*.

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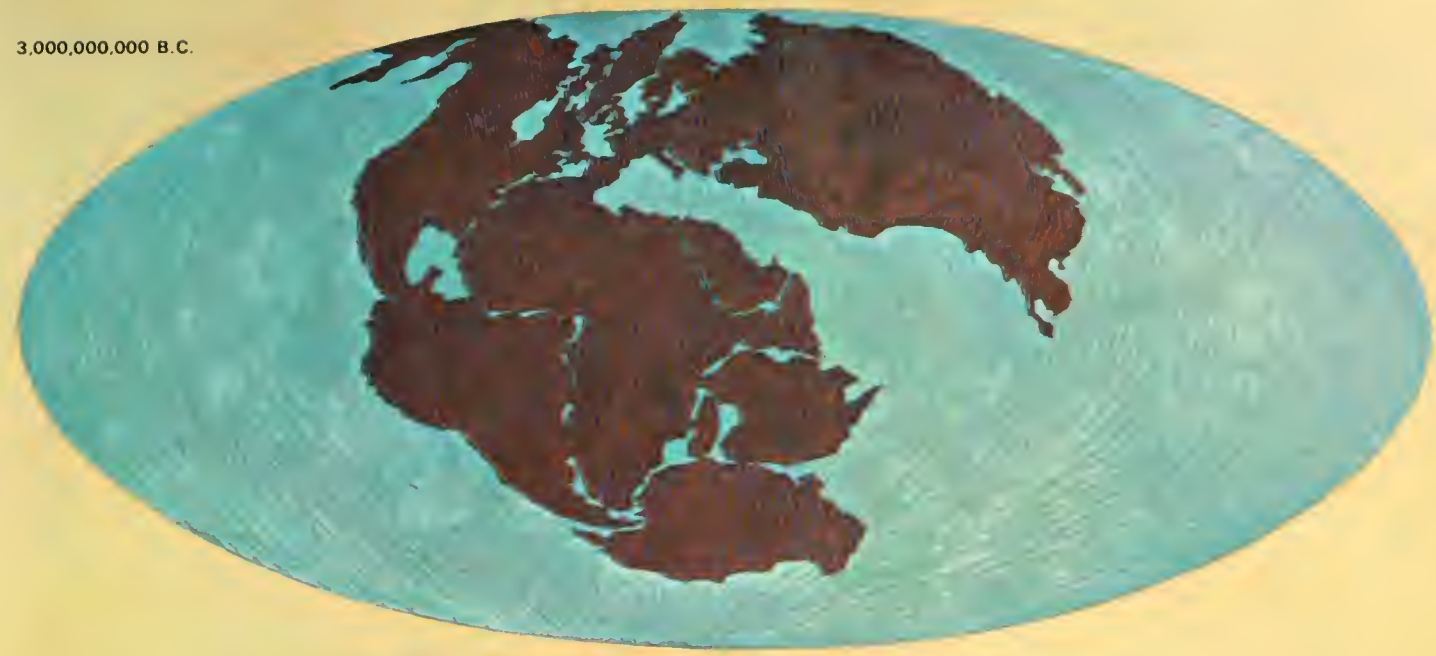

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Measuring the Distant Spheres

Galileo's 1609 telescopes, the first used widely in astronomy, magnified up to 20 times.

ONE OF THE GREAT ACHIEVEMENTS of the human intellect is the surprisingly intimate knowledge of the planets that has been deduced simply by studying them, with one device or another, from many millions of miles away. Although the rapid improvement of space technology is now beginning to make firsthand study possible, for many years to come the great bulk of information about the solar system will continue to be derived from electromagnetic waves that cross the vacuum of space needing no vehicle or medium in which to travel.

Fortunately these talented waves exist in great variety, each kind with its special usefulness. Visible light is one part, but only a small part, of the electromagnetic spectrum. At one end of the spectrum are radio waves many miles long; at the other end are gamma rays whose waves are shorter than one billionth of an inch. Between these extremes, in order of decreasing wavelength, are the shorter radio waves and microwaves used in communication; infrared light of many kinds; ordinary visible light, ultraviolet light and X-rays. Although waves of different lengths come from different sources and have different characteristics, they all travel at the same velocity—186,000 miles per second—and they all yield information if disentangled with skill and subtlety.

In the detailed observation of the planets the naked human eye is not much use. It is a masterpiece of evolution and beautifully designed for its natural purpose, which is to keep its owner in touch with his rapidly changing surroundings, but for most kinds of astronomy it is a blunt instrument. The visible light to which it is sensitive is only a tiny segment of the electromagnetic spectrum. The eye is totally blind to all the rest. Its ability to separate close sources of light and thereby to see fine details, called its resolving power, is coarse. Many familiar stars, such as Mizar in the Big Dipper, show themselves to be double in the simplest telescope. The eye sees them as single because it fails to resolve objects that are closer together than one minute of arc, which is one thirtieth of the angular diameter of the full moon. It is a marvel of human ingenuity that the general plan of the solar system was worked out so correctly by the naked eye before the appearance of the telescope, to which astronomy owes its rapid modern advance.

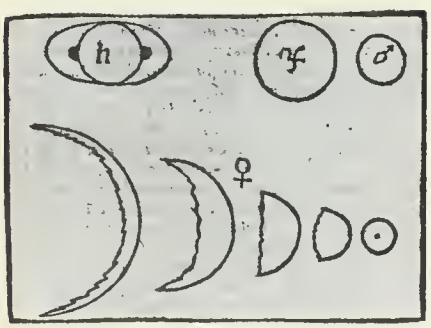
The telescope was the product of Dutch spectaclemakers who had been grinding lenses for generations without understanding quite how they worked. A few years after 1600 one of them, possibly a man named Lippershey, discovered by happy accident that two lenses of the proper curvature, held the proper distance apart, make distant objects look larger. Galileo was the first to put the fascinating invention to serious work in astronomy.

Galileo's instruments were crude; the first one had a magnification of about three diameters. But when he turned them on the sky in 1609, they vastly enlarged and enriched the universe known to man. Marvel after marvel streamed through the little tube. Among the first major discoveries were the four bright satellites of Jupiter. Venus, his next triumph, proved to have phases like the moon's. He well understood the

importance of what he was doing. "I am quite beside myself with wonder," he wrote to a friend in 1610, "and I am infinitely grateful to God that it has pleased Him to permit me to discover such great marvels as were unknown to all preceding centuries."

Modern telescopes, particularly the larger ones, may use curved mirrors instead of lenses, but they all operate on the same optical principles and they all perform two services. First, they improve the eye's resolving power, its ability to see fine details. The objective (front) lens forms at its focus an upside-down image whose size depends on its distance behind the lens. The image can be made directly visible by putting a sheet of frosted glass at the focus. The picture is generally very small, but it is a captive in the telescope tube and can be examined by an eye lens that acts as a microscope and enlarges it to any desirable size, just as a regular microscope turns a barely visible insect into an armored monster. The image of Mars, which looks like a small reddish dot, can be magnified enough so that its spread-out markings are seen separately by the coarse-grained human eye.

GALILEO GALILEI, the great Italian astronomer, pointed his telescope skyward in 1609 and obtained a new view of the universe. In the drawing below, made from precise observations, Galileo verified the theory of Copernicus that Venus has phases like the moon's. Above Venus, from the left, are Saturn, Jupiter and Mars.



Squeezing light for the eye

The second service of a telescope is to gather light. The pupil of the eye is never more than a third of an inch in diameter, and all the light available to it must pass through this small opening. A telescope's objective lens is the equivalent of the eye's pupil. The difference is that it is bigger and therefore gathers more light, and it packs this light into a bright bundle of rays that is slender enough to enter the pupil, thus making available to the eye more of the light emitted by the source. This makes objects look proportionately brighter. The 200-inch aperture of the Mount Palomar telescope, the world's largest, concentrates 360,000 times as much light as the eye; if it were pointed at the sun and used as a burning glass (which is not likely), it would melt a sizable hole in a firebrick.

Telescopes as such, no matter how big and well designed, are only the beginning of astronomical technology. Equally important is photography, which betters the eye's action in additional ways. When photographic film is placed at the focus of a telescope, the whole telescope acts as a camera, and the film makes a permanent record that can be studied at leisure and referred to later.

Even more important, the film's image is not formed in an instant, as the eye's is. It is cumulative, building up like a pencil drawing made blacker by retracing. A telescope-camera can follow all night—or even for several nights—the motion of the same dim object while its feeble light builds up a picture on the film. The spiral arms of galaxies grow, hour by hour, reaching far out into intergalactic space. The most spectacular pictures of the deep sky are made by very long exposures.

Looking at astronomical objects with a telescope or making photographs of them utilizes only a small part of the information contained in light: its direction and its relative intensity, which together form images

of the objects on the eye's retina or the camera's film. But if light is taken apart into the many wavelengths that it normally contains, other kinds of information can be extracted. To accomplish this analysis, light must be examined with a prism or a grating of finely ruled lines in an instrument called a spectroscope, to which man owes an important part of his knowledge of the universe.

A rainbow from the planets

Everyone has seen a rainbow, and most people know that when sunlight passes through a prism it spreads out into a rainbow pattern of colors. Each color contains a group of wavelengths, and together they extend from the shortest waves in the visible violet to the longest in the red. The colors as seen by the eye do not yield much information because the eye is not equipped to distinguish small differences in wavelength. But if sunlight is passed through a narrow slit and then spread out by a prism, its rainbow spectrum is crossed by thousands of bright or dark lines. Each line is an image of the slit in light of a slightly different wavelength, and each has a story to tell about the place it came from.

The bright and dark lines are a cryptogram that science has learned to interpret with great precision. When a gas, for instance, is heated so hot that it gives visible light, that light is concentrated in a limited number of wavelengths, so when it is examined with a spectroscope it separates into a spectrum made up of individual bright lines. This spectrum is different for each chemical element. The bright lines it contains—their number, relative brightness and specific wavelengths—identify the element as positively as fingerprints identify a man. When a known pattern, or a recognizable portion of one, is found in a spectrum, the element responsible can be identified. And often an estimate can be made of its abundance in the source of light.

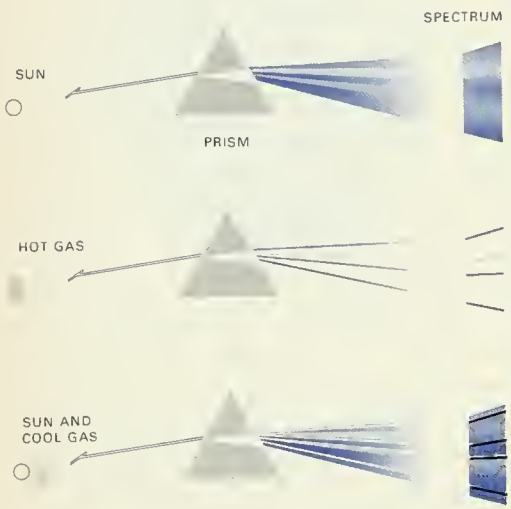
The dark lines have a closely related origin. Under certain conditions an element can absorb light instead of emitting it. The wavelengths it absorbs are the same ones that it can emit. Thus when a spectroscope analyzes light that has been partially absorbed by a substance while passing through or reflecting off it, a second type of spectrum is obtained. This absorption spectrum consists of dark lines, and they create a pattern identical to the pattern of the element's bright emission lines.

By comparing these sequences of bright or dark lines with the spectra obtained from known substances on earth, astronomers can tell what stars are made of. This same technique can be applied to the planets, although not quite so readily as to stars, since planets give no visible light of their own, merely shining by reflected sunlight. But materials in their atmospheres or on their surfaces do absorb parts of the solar spectrum and so betray to some extent their chemical composition.

If any proof is needed that the moon is not made of green cheese, spectroscopy supplies it: years ago, Professor R. W. Wood of Johns Hopkins compared the moon's spectrum with that of green cheese and found, not to his surprise, that they are quite different.

Planets are comparatively cool and so emit little radiation of their own. That which they do emit is almost entirely infrared. Astronomers can turn a telescope on a planet and measure with delicate instruments the degree to which detectors here on earth are heated by certain selected infrared wavelengths emitted by the planet. The "infrared brightness temperature" of the planet can then be computed. It is the temperature that the planet must have in order to deliver to the earth the amount of infrared power that the instruments have detected. This temperature might refer to the planetary surface or the cloud layer, depending on which is the source of the infrared radiation emitted to space.

The waves that tell so much about planets must pass through the earth's atmosphere before telescopes convert them into spectra and images. That trip is, for many of the waves, a rough one. Astronomers, as people, may admire the blue of the sky and derive pleasure from sunset clouds, but in a professional way they find the atmosphere an annoyance. They think of it as a stifling blanket that shuts off most of the information that the universe is trying to feed into their instruments. Worse, it is a moving blanket; it crawls and writhes with turbulence like the air above a hot pavement and distorts the light that manages to struggle through.



SPLITTING LIGHT into its component colors —a technique called spectroscopy—is one method astronomers use to identify atmospheric molecules on distant planets. When the light comes from dense hot gas, like the sun, a prism separates it into a wide spectrum of colors (shown at top as shades of blue) with each color representing specific wavelengths of light. A luminous, less dense gas *(center)* emits only a few wavelengths, producing a widely separated spectrum. But when the same gas is cool and sunlight passes through, its molecules absorb the wavelengths they would normally emit, and the resulting spectrum has dark lines, which allow astronomers to identify the molecules in the gas

When the stars dance

Even the clearest nights, when the sky is velvety black and the stars sparkle like jewels, are often useless for serious observing. Star images dance like gnats, and the markings on the faces of planets merge into shimmering blurs. Astronomers call this condition "bad seeing." It can be avoided to some extent by putting observatories on mountaintops in arid regions, where clouds are infrequent and much of the turbulent atmosphere is left below. But even in the best locations, bad seeing sets a limit on the finest telescopes.

Because of bad seeing, the direct human eye still has an honored place in planetary astronomy. Photographing a planet, even with a large telescope, needs a considerable exposure time during which atmospheric turbulence smears the image and obscures fine details. But the quick-seeing eye of a human observer at a telescope can watch a planet night after night, waiting for rare intervals when the atmosphere happens to be steady. Then for an enchanted instant the face of the planet comes uncannily clear. Tantalizing markings spring into view, and quickly fade again. If the observer is trained and skilled, he can sketch some of these features before they disappear.

Even if the atmosphere were always perfectly steady, it would still be a barrier. The air on a clear, bright day looks transparent because the eye is sensitive only to certain wavelengths of electromagnetic radiation —those of visible light—that are not absorbed. To other kinds of radiation the atmosphere is as opaque as heavy smoke. Astronomers describe this condition in a rather curious way by saying that the light the eye sees passes through the "visible window" in the atmosphere.

The atmosphere might be compared to an opaque barrier laid over the entire spectrum of electromagnetic waves. In this barrier are openings, or windows, each corresponding to a specific range of wavelengths at different parts of the spectrum. One of these windows admits visible light; another admits a particular group of infrared wavelengths. Wavelengths that fall between the windows do not get through.

These varieties of light are detected and recorded by astronomers with techniques that are roughly analogous to the way the human eye responds to visible light. But the atmosphere has another broad window, and through it come waves that must be treated in an entirely different manner. No known earthly creature has natural sense organs that take advantage of them. These waves are so long that they are radio waves and they must be "seen" with a radio receiver.

The radio window

In 1931 Karl Jansky of Bell Telephone Laboratories was investigating a kind of radio noise or static that interferes with long-distance radio communication. The noise was caused by radiation that was familiar in wavelength, but he found it was coming from outside the atmosphere. Jansky's discovery marked the birth of radio astronomy, which is now a technique almost as important as astronomical observation through the visible and infrared windows.

The radio window in the atmosphere does not permit all radio waves from space to reach the earth's surface. Microwaves of wavelength appreciably shorter than one centimeter (0.4 inch, used in some radars) are absorbed by water vapor in the atmosphere. If the waves are longer than about 15 meters, they are reflected back into space by the same electrically charged layers that guide man-made radio waves around the curve of the earth. But the radiation between one centimeter and 15 meters, which does pass through the radio window, brings a wide variety of information not provided by optical astronomy.

Radio telescopes are fundamentally different from optical ones. They do not form an image of the planet or other object at which they are pointed. Usually they concentrate radio waves from the planet as a whole on a detector so the intensity of the radiation at various times can be recorded in some handy form such as a wiggly line on a moving strip of paper. Often the telescope remains fixed and the earth's rotation swings it across the sky until it points directly at a source of radio waves. A large peak then appears among numerous lesser wiggles on the paper. The height of the peak tells how much radio energy is being received from the source at the wavelength to which the telescope is tuned. The mere existence of the radio-signal peak proves that *something* is out there—a fact that in many cases can be established no other way—and its wavelength may hint at what the something is. But most important, the strength of the peak can be used to calculate the temperature of the object. In this way radio telescopes serve as thermometers. They also detect the presence of magnetic fields by noting the radiation given off

ABSORPTION LINES, patterned by molecular activity *(opposite page)*, are studied by astronomers for clues to a distant planet's atmosphere. Sunlight *(blue)*, with some of its wavelengths already absorbed by the solar atmosphere *(dark lines)*, reflects off the planet's surface, gaining more dark lines as other wavelengths are absorbed by the planet's atmosphere. Still more lines appear as the light passes through the earth's atmosphere. Confronted with a spectrum whose dark lines represent absorption by three different atmospheres, astronomers eliminate the lines known to be contributed by the sun and the earth. The rest can be used to identify the gases of the planet's atmosphere.

by the charged particles moving within the fields.

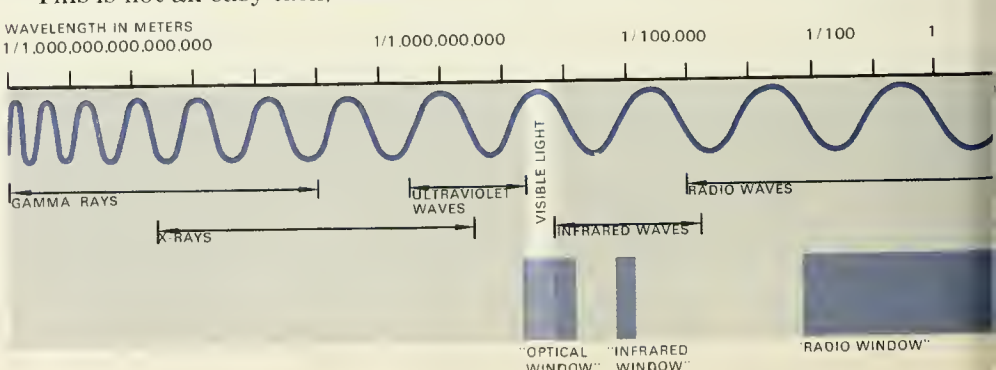
For studying the planets, radio astronomy is proving extremely useful, making up to a considerable extent for the fact that planets do not emit visible light of their own. The materials the planets are made of emit radio waves. And these waves, unlike visible light, easily penetrate planetary atmospheres and cloud layers. The first evidence that the temperature of the surface of Venus exceeded 600° F. was detected by the radio telescope of the Naval Research Laboratory, Washington D.C., in 1956. The belts of high-speed charged particles that surround Jupiter, similar to the earth's Van Allen belts, were a mystery until the radio waves they emit were traced to their source by two 90-foot radio telescopes at California Institute of Technology.

To the moon and back in 2.6 seconds

The traffic in radio astronomy is not all one-way. The great dish-shaped antennas used to collect signals from space can also be used as powerful radars to send waves into space and then listen for echoes reflected from anything they hit. The moon is an easy target for this sort of probing. A wave goes out and bounces back in 2.6 seconds as a strong signal. These waves first proved that the lunar surface is not steep and rugged. Radar bounced off Venus or Mars takes several minutes to make the round trip, and the reflected waves are extremely weak when they reach the earth. But by accurately timing these faint echoes, radio astronomers can now sense prominences on planetary surfaces and even follow them as they rotate with the planets. Already this kind of radar surveying has revealed what seem to be mountains on Venus, and has settled a long-standing dispute about Mercury: that planet does not, as had been thought, keep the same face permanently toward the sun. Radar astronomy is developing rapidly. It is the only way (short of a space voyage) that planets can be subjected to active probing, not mere passive observing, and great future discoveries are hoped for it.

Astronomers are duly grateful for their radio window, but still they are not satisfied. They would like to stop peering through windows and get out into the great outdoors. Beyond the atmosphere the whole electromagnetic spectrum from gamma rays to mile-long radio waves bombards the earth from space, crisscrossing in every direction and freighted with information about undreamed-of wonders. Much of this treasure does not penetrate the atmosphere and is therefore beyond the reach of ground observatories. The hopes of many forward-looking astronomers center on establishing observatories outside the atmosphere, a step that may be as fruitful as the invention of the telescope or the development of radio astronomy.

This is not an easy task; astronomical instruments are both large and



ELECTROMAGNETIC WAVES, indicated by the wavy lines in this schematic drawing, are emitted by the sun and, to a lesser extent, by the planets. While the great majority of radiation wavelengths are blocked by the earth's atmosphere, certain wavelengths are admitted through atmospheric "windows" *(blue shading)*. From these limited ranges of radiation astronomers have gained almost all of their information about planets. Optical telescopes collect most of the rays entering through the "optical window," which admits the light we see and extends slightly beyond into neighboring wavelengths. The longer wavelengths coming through the "infrared window" can be recorded by special heat detectors, while the even longer wavelengths of the "radio window" require radio receivers. Other wavelengths may be examined only by means of equipment lifted above the earth's atmosphere.

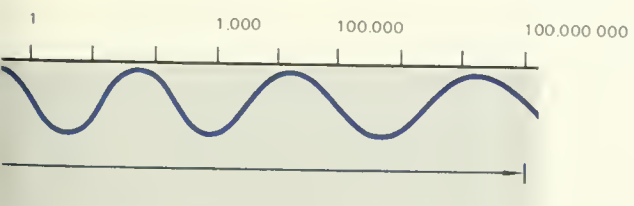
delicate, and most of them require extremely steady pointing. But a good start has been made. Telescopes and other instruments of moderate size have been lifted by giant balloons into the upper atmosphere, leaving far below all of the turbulence that causes bad seeing as well as almost all of the water vapor and most of the carbon dioxide that block important regions of the spectrum. The first convincing evidence of water vapor on Venus came from infrared light that was intercepted by a balloon-borne spectrometer before the earth's atmosphere could absorb it.

An orbiting observatory

The simplest way to get instruments above most of the atmosphere where they can avoid most of its absorption is to load them on a rocket and shoot them to an altitude of 50 or more miles. This has been done to record the ultraviolet portions of planets' spectra. Some valuable information has been gained in this way, but the rockets do not hold still. A much firmer mount would be provided by a satellite. Once it had settled into its orbit around the earth and its initial rolling motions had been stopped, it could keep its telescope pointed accurately at the same target for any desired length of time. It would always have perfect seeing, and by proper choice of instruments it could extract information from the entire electromagnetic spectrum. A family of such orbiting astronomical observatories, with 36-inch or larger telescopes, is scheduled to search the skies in the 1970s. Much larger ones—including a radio telescope about 12 miles across—are proposed for the more distant future.

Some of the greatest successes in new-style astronomy have been achieved by unmanned spacecraft that cruise close to planets and transmit the data and pictures that they have gathered back to earth by radio. One of these, the Soviet Venera IV, detached a small capsule that entered the atmosphere of Venus and transmitted data from deep within it. The dramatic television pictures transmitted by U.S. Surveyor III, which landed on the moon, showed objects as small as grains of table salt, and instruments on U.S. Surveyor V made a partial chemical analysis of the moon's soil.

These first attempts for a close look at the planets are only the prelude to direct exploration by human observers. The first Astronauts who make a landing may not learn very much that is new during their brief, harassed and encumbered visit. They will be in competition with hardy, sensitive, expendable instruments that will have preceded them. But the great scientific value of landing men on the moon or planets is the unforeseen observations and experiments that they will be able to perform when their pace becomes less hectic. No instrument designed in advance on the distant earth can exploit new opportunities on these strange worlds as well as human beings can.



The Tools of the Astronomer

The astronomer has always been like a small boy pressing his nose against a candy-store window: he could see uncountable tempting delights spread before him, but they were tantalizingly out of reach; he could neither smell nor taste nor touch. As a result, he developed an extraordinary variety of ingenious tools and techniques to help him sample from a distance. He has used optical telescopes to magnify and brighten the planets so that their features could be examined. Huge radio telescopes have helped him take the planets' temperatures. With analyzing devices he has dissected planetary light and has thus detected the presence of such substances as hydrogen, ammonia and methane.

Within the past few years the space age has partially opened the door to the candy store. Today balloons float almost to the top of the atmosphere for a more distinct view of the heavens; rocket-borne cameras snap revealing close-up photographs of the moon and Mars. With almost every month that passes, instruments and Astronauts are drawing closer to the planets—looking toward that day when man will confront distant objects that have tantalized him for ages.

A GIANT EAR TO THE SKY

The world's largest fully steerable telescope, at Jodrell Bank in England, listens for radio signals with its 250-foot-wide dish antenna. The dish bounces radar signals off planets and measures their distance from the earth. It was this equipment that first gave Western scientists the pictures transmitted by the Soviet spacecraft Luna IX after it landed on the moon in February 1966.

REACHING FOR A RAINBOW
The 76-inch reflecting telescope in Haute Provence, France, has analyzed infrared light from Venus, Mars and Jupiter. Light captured by the instrument passes down through the narrow tube at the lower left to a spectroscope located in the basement of the observatory

The Great Gatherers of Planetary Light

In 1609 Galileo turned a toylike telescope toward the heavens and, to his delight and amazement, perceived that Jupiter had satellites and Venus displayed phases like the moon's. These were only the first astonishing sights that the telescope's extension of human vision was to provide. Later astronomers would discover the new planets Uranus, Neptune and Pluto, and would detect gases emitted from the moon.

Simple telescopes like Galileo's—a front lens concentrating light into an image that can be viewed with an enlarging lens—are still used. But the great observatories employ huge instruments in which the front lens is replaced by a curved mirror. These mirror telescopes are more effective for studying dim planetary light with another of the major tools of modern astronomy: the spectroscope. This instrument breaks up the light reflected by the planets into identifying patterns, called spectra, which enable scientists to determine the chemical makeup of planets from a distance.

A HUGE EYE TO THE HEAVENS
The giant telescope at Mount Palomar, California, with its 200-inch mirror (in the round, basketlike housing at lower center of picture), is the largest on earth. It has been used to measure the temperatures of the surface of Mars and to search for organic matter on the same planet.

STUDYING THE ATOMS' AUTOGRAPH
In the basement of the Haute Provence observatory, a technician adjusts a spectroscope that is recording the spectrum of light reflected from the planet Jupiter. As the light passes through the instrument, it is separated into its component colors to make the pattern at the right. The dark lines indicate absorption of light by atoms and molecules, the one indicated by an arrow is identified by its position as the line of ammonia.

FOCUSING RAYS FROM SPACE

At the University of Arizona a telescope *(right)* gathers infrared radiation from the planets with a 60-inch parabolic aluminum mirror (in the housing at center). The mirror focuses the radiation on a detector that precisely measures planetary temperatures millions of miles away.

COOLING A HEAT MEASURER

Dr. Frank Low pumps liquid helium into a vacuum bottle housing a device he developed, called a germanium bolometer. The instrument is able to detect a hundred-trillionth of a watt of infrared radiation, equivalent to sensing the glow of a lighted cigarette 10,000 miles away.

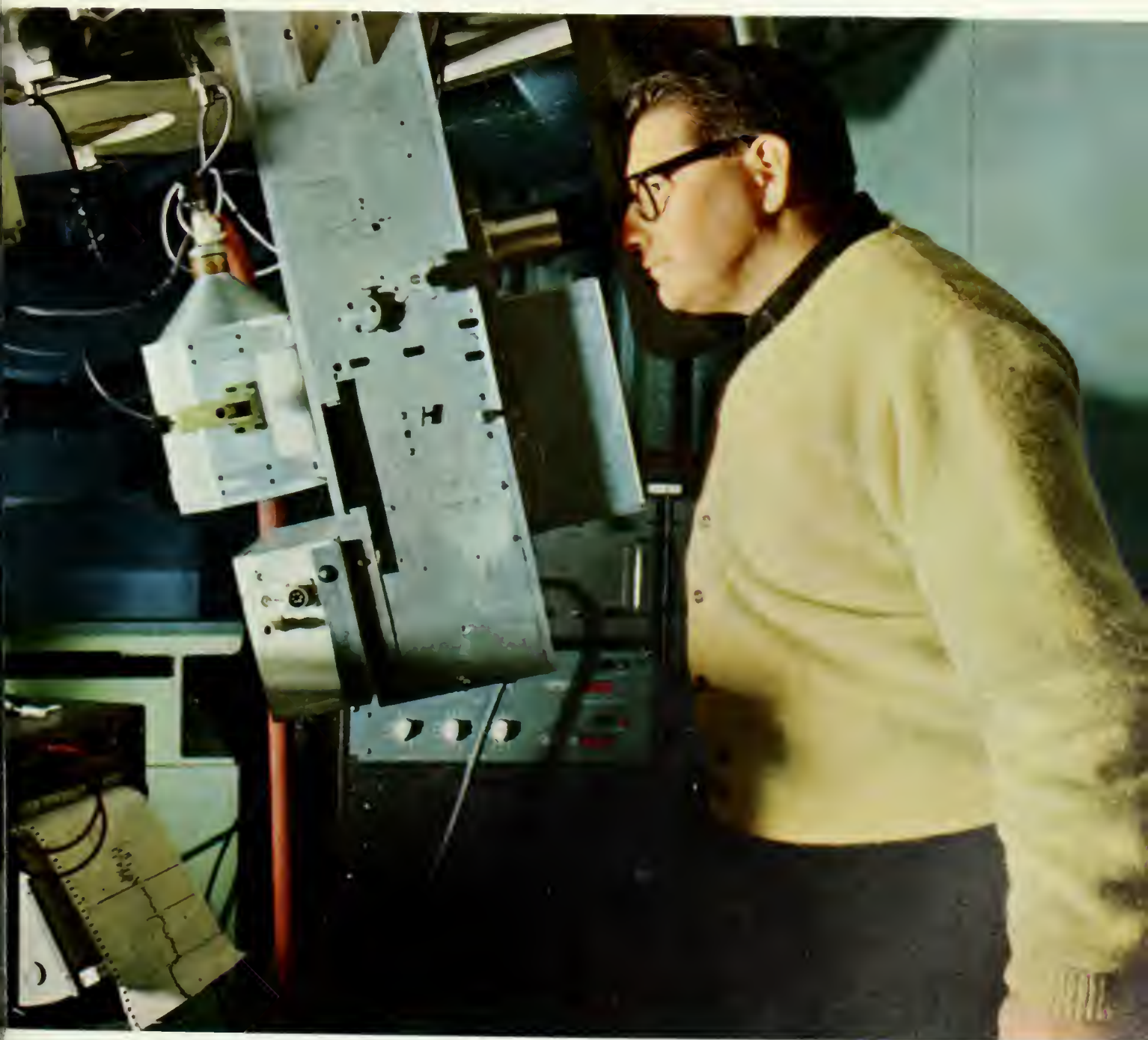
A COOL READING FROM JUPITER

As Dr. Low sights the telescope *(below)* on Jupiter, the germanium bolometer inside the bottle at the center of the picture registers the distant temperature as a tracing on a chart. This infrared-detection technique has measured temperatures on Saturn and the moon.

Taking the Planets' Temperatures

With delicate electrical thermometers connected to their telescopes, astronomers have learned that temperatures on the planets are extremely severe. Mercury gets as hot as 780° F., while Pluto may be as cold as −360° F. But more precise measurement of these distant temperatures reveals new facts about the planets—such as surface dustiness.

One of the most sensitive of the thermometers for the planets is a germanium bolometer, developed by Dr. Frank Low of the University of Arizona. At its heart is a tiny crystal, which responds to slight temperature variations with changes in electrical resistance. Dr. Low's bolometer has found that Jupiter's temperature above the clouds ranges from −190° F. to −225° F. Cold as that may seem, it was many degrees higher than expected, suggesting to him that Jupiter emits heat of its own.



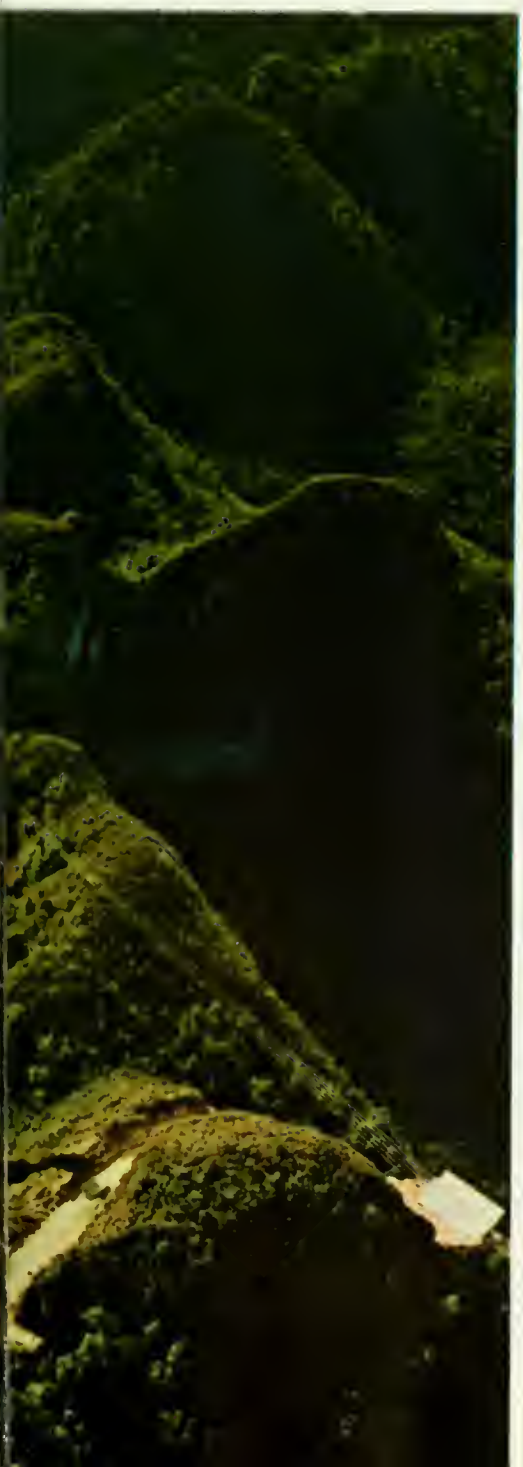
Deep Dishes and Tandem Detectors

Among the most valuable sources of information about the planets are the radio waves they emit. From the intensity of the waves it is possible to deduce the temperatures of planetary atmospheres, and from the length of the waves the depth within the atmospheres of radio sources. Most important, radio waves bring data that visible light does not—clues to magnetic fields, for instance.

The telescopes used for observing these waves are not telescopes in the usual sense, but extremely delicate radio receivers with huge antennas: the world's largest *(below)*, near Arecibo, Puerto Rico, covers 18½ acres. Enormous dish antennas like Arecibo's are the best devices for picking up weak radio signals, but more accurate mapping of signal sources is possible with a pair of antennas *(opposite)*. A radio telescope can also "feel" the planets by bouncing radar signals off them. Often the results are a surprise: radar from Arecibo tracked the edges of Mercury as the planet rotated, and proved that, contrary to a long-held belief, it does not always keep the same face to the sun.

A PAIR OF PINPOINTERS
The radio telescopes at Caltech's Owens Valley observatory *(right)* work in tandem to distinguish among planetary radio sources. By mapping the origins of radio waves from the regions around Jupiter, this observatory located belts of charged particles surrounding the planet

COLOSSUS IN THE VALLEY
Arecibo's dish *(below)* is a reflector, focusing natural radio signals from space onto a detector in the carriage suspended from the towers. When the telescope serves as radar, a man-made wave is sent from carriage to dish to planet, then bounced back to dish and carriage.



A TROUGH FOR DISTANT SIGNALS
The huge trough of the University of Illinois radio telescope *(above)* dwarfs four men standing in its center. Equal in size to more than five football fields, the trough can detect weak radio signals from far out in space. It has received faint signals from beyond our galaxy, the Milky Way, and has also studied radio wavelengths within the solar system from the planet Jupiter.

Tracking Whispers from a Venus Flight

The age of the rocket marked a major turning point in the science of astronomy. Since the early 1960s far-ranging space vehicles have been sending back a wealth of radio data from the reaches of space. But the transmitters are so small and the distances so vast that the signals received on earth are very weak. Collecting them calls for an elaborate base like this one at Goldstone, California, known as the Deep Space Instrumentation Facility of the Jet Propulsion Laboratory. Goldstone's big radio telescopes relay their signals to a computer; together, the two instruments pick up the faint radio whispers, record the information in their complex variations, diagnose ailing instruments and transmit commands out to the space vehicles.

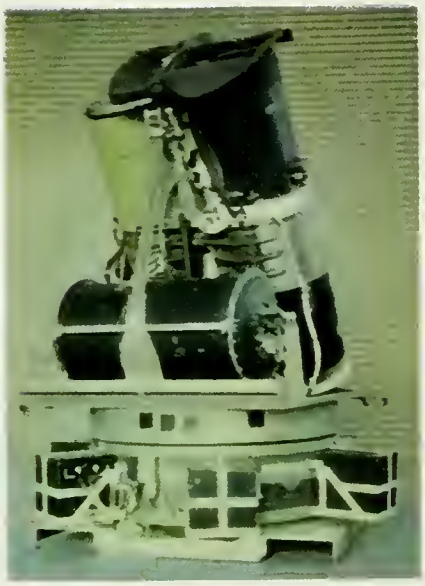
The signal received from space is

a "carrier beam" that has been made to change in a number of ways so that it can convey many different items of information—almost as if it were a clothesline carrying assorted items from the family laundry. The carrier may include signals that indicate the speed, course and position of the space vehicles, a burned-out battery or a stuck switch, plus data from several kinds of instruments.

The Goldstone station is the only one of its kind in the United States. It has two 85-foot radio telescopes and a 210-foot dish, so powerful that it is expected to track flights to Pluto, 3.58 billion miles away. Four similar stations located in Canberra and Woomera, Australia, Johannesburg, South Africa, and Madrid, Spain, work with Goldstone to keep constant contact with U.S. deep-space probes.

A MESSAGE FROM MARINER
A coded message from Mariner II comes out of a teleprinter. The code is in the form of letters and symbols, which the computer translates into physical measurements. If a symbol is repeated for an entire line on the print sheet, it indicates that an instrument is out of order either within the spacecraft or on the ground.

MONITORING SIGNALS FROM SPACE
Engineers at the Goldstone tracking station listen to signals from the Venus-bound spacecraft Mariner II as they are picked up by the radio telescope outside. Almost immediately a computer begins to convert the signals to a number code that indicates how well Mariner is working.



A BALLOON'S DELICATE CARGO
A motor-steered telescope and a spectroscope *(above)* are the main instruments that were carried into space by a Johns Hopkins University balloon to measure infrared radiation reflected by the clouds and upper atmosphere of Venus.

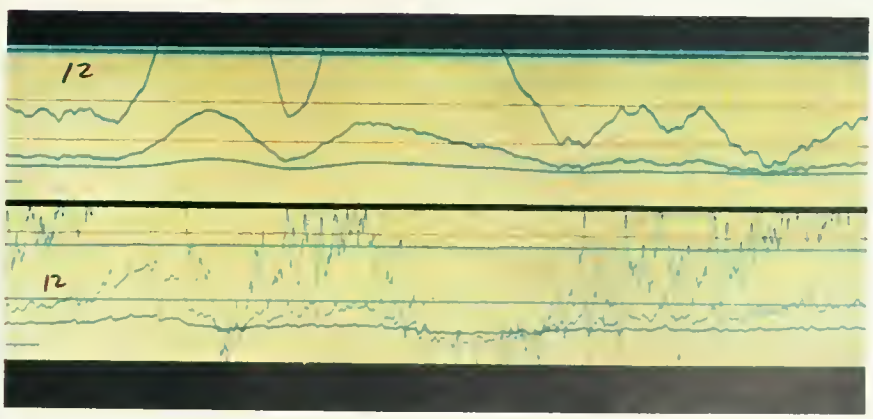
GASSING UP FOR A HIGH RIDE
A balloon takes in lighter-than-air helium at Holloman Air Force Base in New Mexico before being launched by a special truck *(right)*. The balloon material, made of plastic only 2/1,000 inch thick, can lift a one-ton astronomical instrument package to an altitude of almost 90,000 feet. At that level the atmosphere is so thin that the balloon, which is almost collapsed at launching, expands to a diameter of 202 feet

A Balloon's-Eye View of Planets

The earth's own atmosphere is the chief obstacle to a clear view of the heavens. The reason stars twinkle and the images of planets shimmer is that the air swirls and roils like a stormy sea. Astronomers have tried to escape this interference by building observatories on mountaintops, above most of the turbulence and clouds. Even up there, absorption of light by ozone, carbon dioxide and water in the atmosphere blocks the scientists' observation of most infrared and ultraviolet radiation.

Only when the first automatically guided telescopes were sent aloft on balloons in 1959 were these limitations of the atmosphere partly overcome. By means of balloons, thousands of pounds of instruments at a time could be raised almost entirely beyond the atmosphere. Guided by devices that automatically sighted on stars or the sun, the balloon-borne telescopes have tracked Mars, Venus and Jupiter, giving scientists some of the most unusual analyses they have ever had of planetary atmospheres.

TOWARD THE ATMOSPHERE'S LIMIT
The balloon-borne instrument package of the Johns Hopkins Venus project rises into the sky This balloon reached an altitude of 16½ miles, there, free of most of the atmosphere's absorption, it detected water vapor near Venus' clouds



EVIDENCE OF ICE FROM VENUS
The wiggly lines on the graph above contained an important clue for astronomers Obtained during a 1964 balloon flight, the lines reflect the intensity of specific infrared waves—evidence for ice crystals in Venus' cloud deck The Venera IV probe later detected water vapor below the clouds Since water and ice block heat loss, these findings explain why Venus is so hot.

LNO	171	172	173	174	175	176
100	35	36	36	36	36	37
101	33	34	34	33	34	34
102	33	34	34	33	34	33
103	33	33	33	33	33	33
104	33	34	33	34	33	33
105	33	34	34	33	34	34
106	33	34	34	34	34	34
107	33	33	33	34	35	34
108	33	34	34	34	34	34
109	34	33	34	34	34	34
110	33	34	33	34	33	33
111	33	34	34	34	34	33
112	33	34	35	34	34	34
113	33	34	35	34	35	34
114	33	34	35	34	35	34
115	32	34	33	34	34	34
116	33	34	33	34	34	34
117	33	33	34	33	34	34
118	32	33	34	34	35	34
119	33	33	35	34	35	34

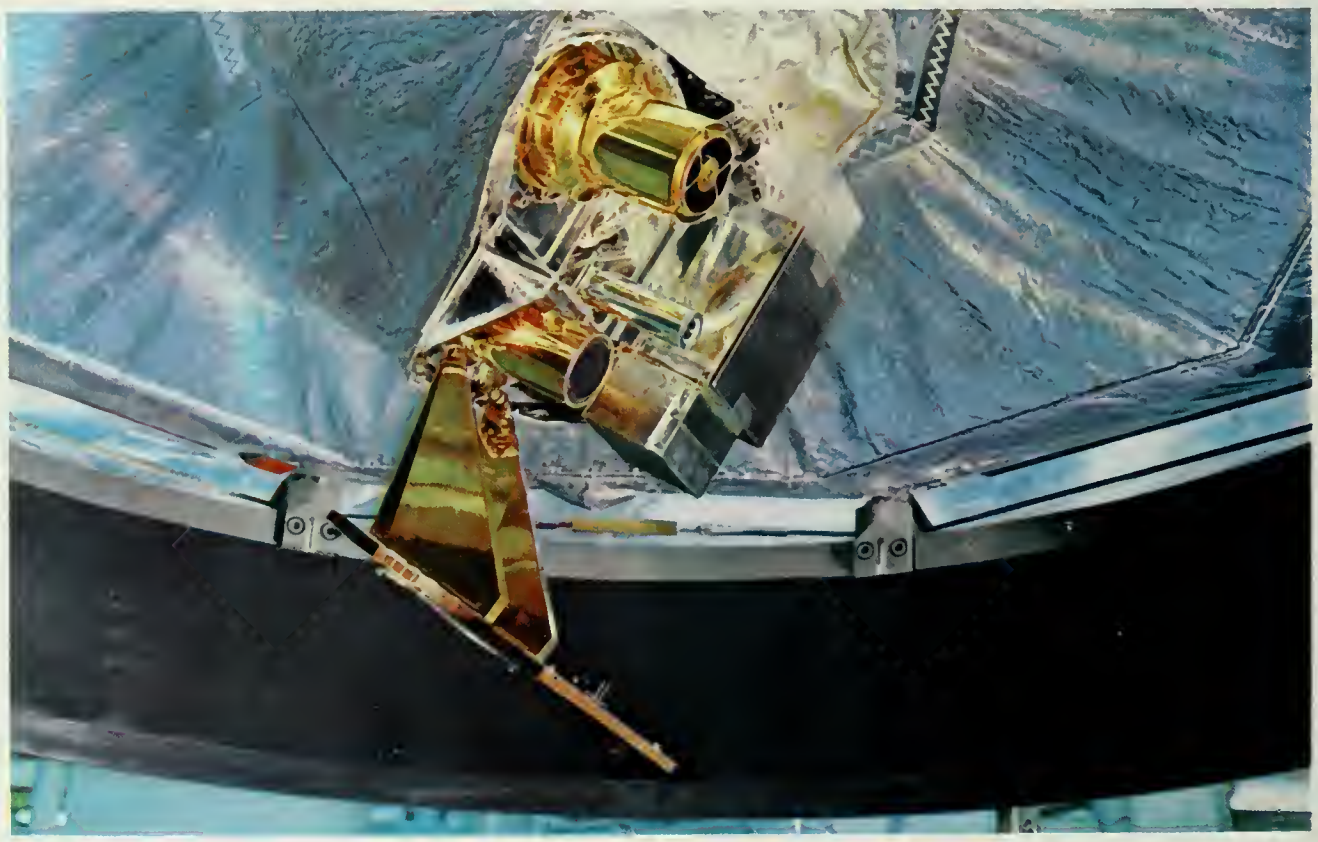
A PICTURE BY NUMBERS
Mariner IV flashed back a series of numbers, each representing the intensity of spots of light on a television screen. When the numbers were translated, a picture of a part of Mars emerged

Preflight Check for a Mars Mission

The pitted regions of Mars, the blazing deserts of Venus, the frothy surface of the moon—such explicit details were confirmed only by sending complex instruments far from earth to examine the planets at close range.

Among the most ambitious of these probes was that of Mariner IV, some of whose equipment is shown here. This vehicle, launched in 1964 to reconnoiter Mars, was 575 pounds of rocket-propelled laboratory. After it streaked through space for seven and a half months, almost four times longer than Columbus spent sailing to America, this spacecraft passed within 6,118 miles of Mars. Fastened to its chassis of magnesium and aluminum alloy were 31,696 electronic components. During the long journey, these instruments detected solar protons, recorded interplanetary dust, beamed radio signals to earth through the Martian atmosphere and determined its density, searched for a weak magnetic field around the planet, televised closeup pictures of the Martian surface back to earth, and captured photographic evidence of craters on the planet's surface.

Astronomers immediately began to plan for the day when a far more complex craft, Voyager, is intended to approach Mars, send exploratory capsules down to the very surface of the planet and relay their findings back.



MARINER IV'S TELESCOPIC EYES
The photographic equipment carried by Mariner IV consisted of a telescope and television camera (top tube) and two sensors (bottom tubes) that aimed the camera. Pictures were taken at distances ranging from 10,430 to 8,160 miles away. The total of 22 photographs, covering a 6,200-mile strip *(pages 144, 145)*, showed about 1 per cent of the planet's surface

A HEAT TEST FOR MARINER IV
In a test chamber, technicians check the temperature of the surfaces of Mariner IV. Overhead lamps flooded the craft with the same intensity of ultraviolet and other light waves it would experience in space, thus determining how its parts would stand up to radiation during its trip

4

The Lessons of the Moon

Compiling the first comprehensive geologic moon map, lunar geologist Eugene Shoemaker checks detail maps on the wall and floor.

THE EARTH is a minor planet, but its respectably large moon gives it a major distinction. While all other planets far outrank their satellites or have none, the earth and moon are so close in size that they can be called a double planet. Viewed from Venus or Mars they must be a fascinating sight: a small planet chasing a bigger one across the sky, sometimes ahead of it, sometimes behind, and on rare occasions crossing its face, casting a shadow on it or disappearing behind it. If Mars ever had astrologers, they must have used this stately dance for predicting the future, and the motions of the earth and moon about each other could well have taught Martian astronomers the principles of gravitation.

To human astronomers the moon is one of the most rewarding objects in the skies. They have studied it with telescopes for centuries, and more recently have observed it with rocket-borne instruments that have landed on it. Soon men also will land on its surface. The first Astronauts to climb out of a spacecraft and set foot upon the moon will find themselves in strange and dangerous surroundings. The sky will always be black, even in daytime. The blue of the earth's sky is a consequence of the atmosphere, and the moon has none. The earth, if visible at all, will always hang in about the same part of the lunar sky. It will show phases like the moon's and will rotate entertainingly. Its diameter will appear about four times as great as the moon's does from earth, but because of its greater reflectivity it will give about 80 times as much light. Even a crescent earth will be bright enough to read by, and the cold blue light of the full earth will be sufficient for many kinds of work.

There is no climate on the moon in the ordinary sense. The various climates that are found on the earth depend on the temperature and motion of the atmosphere and oceans. The moon's surface is dry and airless, but surface temperatures vary greatly. Surfaces illuminated by overhead sunlight will be too hot to touch, and during the long night all surfaces will fall close to the normal temperature at which oxygen liquefies (−300° F.). Lunar explorers will have to be very well insulated if they hope to survive either the night or the day.

Lunar shadows will be startlingly sharp and sometimes dangerous. Unless some sunlit surface is reflecting light into them, they will be completely black, and all objects in them will be invisible. An Astronaut who walks into a shadow may stumble into an unseen pit; a hand thrust into a shadow may disappear. If it is left in shadow too long, it will freeze, for lunar shadows are almost as cold as the lunar night.

The Astronauts will probably land in a low-lying level area whose surface promises to be reasonably smooth. They will find little rugged terrain; the landscape will be extremely monotonous. Because the horizon is so close, they may not see the lunar mountains. The curvature of the moon's surface is so sharp that for a man of average stature the horizon is only two miles away.

Even among the lunar mountains the scenery will be dull. Although the peaks are often quite high, most slopes on the moon are rarely steeper than 15 degrees. Peaks are broad-based and rounded on top. (The moon's

reputation for ruggedness comes chiefly from photographs taken in low-angle sunlight, which magnifies the shadows cast by the shallow, sloping topography.) This gentle relief is not surprising in view of the moon's airless condition. If the earth had no atmosphere, there would be no water, wind or ice to carve its features and its surface would probably be just as dull as the moon's.

Man's first landing on the moon will be the triumphant climax of an age-old fascination. As far back as ancient Greece, when the planets were known merely as points of light, the moon was recognized as a sphere, and its changing shape was correctly attributed to sunlight falling on it from varying directions. The time between new moons was measured with fair accuracy, and the fact that the same face is always turned toward the earth with only minor wobblings was noted although not explained. (The modern explanation is, in part, that the moon is not a perfectly symmetrical spheroid. It has a massive bulge which the earth's gravitation attracts like a plumb bob, thus keeping the same hemisphere pointing toward the earth.)

GALILEO'S MOON, one of the first drawings made from telescopic observations, around 1610, has a rough, mountainous surface. Noticing the ragged demarcation line between the dark and light sides of the moon, Galileo concluded, rightly, that the irregularity was caused by high mountains and shadowed valleys. But he erred in suggesting that this topography closely resembled the earth's.

Waterless lunar "seas"

Not much more was learned about the moon until the 17th Century, when the telescope first brought its mountains and circular craters into view. Its dark, smooth-looking areas were thought to be seas and were named accordingly: the Sea of Clouds, the Sea of Rains, etc. Recently new techniques of observation and analysis have shown that the long-studied moon still has fascinating mysteries. Its surface is covered, for instance, with a peculiar substance that behaves like nothing found naturally on earth, and its blotched and pitted face is recognized to be an ancient inscription recording events that happened in the solar system billions of years ago.

The actual origin of the moon is a much-debated matter. Some experts hold that it was formed at the same time as the earth and has been its satellite from the beginning. Others think it was once part of the earth. Still others argue that it was formed at a different time and place out of different material, spent its early youth as an independent planet and later was captured by the earth and reduced to the rank of satellite.

The moon's diameter is about 2,160 miles, roughly one quarter of the earth's, but its mass is only $^{1}/_{81}$ of the earth's. This comparatively low mass and the lunar radius have been critical in the moon's evolution. They have made the gravitational pull at its surface one sixth of the earth's, so objects on it can escape into space more easily. The escape velocity is about 1.5 miles per second. To escape from the earth an object must travel almost seven miles per second.

The ease of escape applies not only to spaceships bringing Astronauts home from the moon but also to gases near the moon's surface. Most gas molecules present there, accelerated by the temperatures prevailing during the moon's long, sunlit day, would get moving fast enough to soar into space and never come back. Thus, if the moon had an atmosphere

early in its history, the gases would long since have escaped. Any additional gas molecules that might have been emitted from its interior over the years would be lost in the same way.

Astronomers have made manful attempts to detect some sort of atmosphere on the moon, but the most delicate tests show nothing but an extremely diffuse halo of electrically charged particles. The density of this ghost of an atmosphere is around one ten-thousandth of a billionth of the earth's. For most purposes the lunar atmosphere might as well not exist. Neither can liquid water exist for long on the moon's surface. It must either freeze in some sheltered cranny or evaporate and escape.

Bombardment from space

With no appreciable atmosphere to shield it, the moon is unprotected against the violence of space. Solar radiation strikes it at full strength with its X-rays and ultraviolet light. In addition, the charged particles from the sun—the so-called "solar wind"—hit the surface, as do low-energy cosmic rays and micrometeorites, those minute specks of dust moving at cosmic speeds. All these varied assailants have been searing the moon's surface for billions of years, while the earth is so well sheltered by its atmosphere and its magnetic field that the very existence of most of these attackers was not suspected until rather recently.

As if in recompense, the moon is immune to another kind of attack. Its airless, waterless surface is not subjected to the powerful wind and water erosion that gnaws the earth's mountains down to their roots in a few hundred million years, nor has the moon experienced the internal movements that are still wrinkling the crust of the earth. Long, parallel mountain ridges, the earth's boldest features, are largely absent.

While the moon lacks the familiar features of the earth, it has others that do not resemble the earth's and cannot be accounted for in familiar earthly terms. There are the wide, dark "seas," or *maria;* the great, ring-shaped craters, which superficially suggest volcanoes but are as much as 150 miles in diameter; and the long, bright rays radiating from some of the craters. What is the nature of all these curious things, so different from earthly topography? There is still disagreement about some of them, and hardly any knowledge about a few, but modern selenography, the science of the moon's physical features, has progressed enough to tell with a good deal of confidence how the moon's face reached its present interesting condition.

The most striking and unusual features on the moon are the gigantic craters that cover much of the surface. In the early years of selenography they were thought to be volcanic, but modern evidence indicates they were excavated by objects impacting the moon from space. Some of the objects were small meteorites like those that frequently hit the earth; others were many miles in diameter, big enough to be classed as asteroids, or small planets, like those that follow orbits between Mars and Jupiter. Still others were probably the nuclei of comets. Whatever their size or

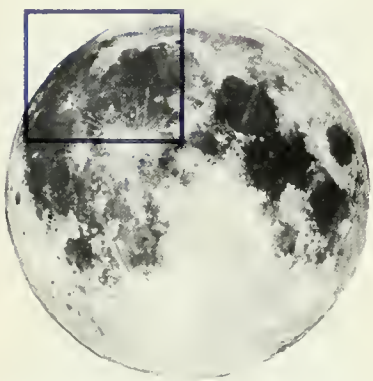
THE MOON'S SURFACE is depicted in these two 17th Century drawings. The illustration above, by Francesco Fontana, was one of the first to include the moon's rays, pinwheels of powdery material splashed out by meteorites as they crashed and formed craters. The drawing below, by Johannes Hevelius, shows the 59 per cent of the moon visible from earth

nature, they hit with enormous speed, and the explosive effect of their impacts blasted craters much larger than themselves.

There is little doubt that meteorite impacts were the most important force in shaping the surface of the moon during most of its history. Their concentrated work can be seen in the bright-appearing "highlands," located mostly in the moon's southern hemisphere, where craters are so crowded that they overlap. These highlands are believed to be the oldest areas on the moon, dating from the youth of the solar system. During this period interplanetary space swarmed with wandering objects of all sizes. In rapid succession they rained on the young moon, building it bigger and bigger and blasting craters that were soon erased by later impacts. The formative period may have continued only a few hundred million years, until the moon (or the earth-moon system) attracted the smaller bodies and swept its orbit almost clear. Then came comparative quiet. Since the moon has no wind or water erosion, the ancient formations have lasted more than four billion years with only minor changes, and are still exposed to view.

The rest of the moon, with its level maria and fresher craters, is not at all like the ancient highlands. Its structures are simpler and more isolated, and they are interrelated in ways that enable experts to determine their comparative ages.

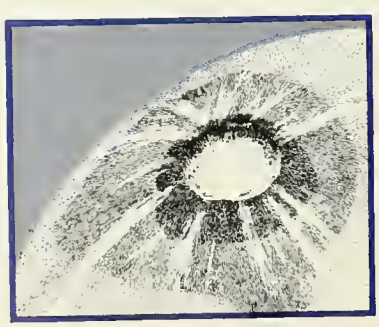
The simplest example of this dating system is the easy proof that the craters known as Tycho and Copernicus are among the youngest major structures on the moon. Each is surrounded by rays streaking outward like the petals of a scraggly flower. The rays overlie everything in their paths, climbing the rims of other craters, marching across maria and mountains. The fact that they are superimposed on other features is proof that they are younger.

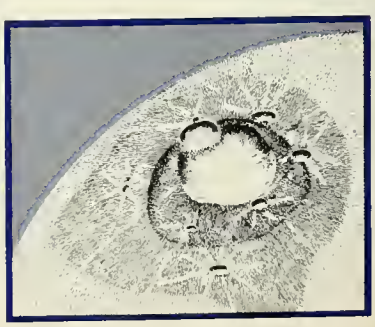


THE SEA OF RAINS, or Mare Imbrium, shown in the square above, was once thought to be a lunar ocean. But astronomers now know that no surface water exists on the moon. Such "seas" are believed to be huge, ancient craters filled with lava, volcanic ash or meteoritic dust. The drawings at right show how the Mare Imbrium region might have been created. First the moon absorbs the impact of a giant meteorite or planetoid. The raised rim of the crater, the rough terrain around it and the light streaks radiating from it were all created by the force of the tremendous impact. Over a period of time *(second drawing)* a number of smaller meteorites crash into the moon's surface, one of them causing the crater's periphery to slump, forming an enlarged basin. The rays of the first crater are obscured by erosion, but those of the newer craters are clearly visible. The third drawing shows the lunar sea after its basin has become filled. Finally there is the Mare Imbrium area as it is seen today, with the newest craters identifiable by their prominent rays.

A collision at 50 miles per second

The rays of a crater are believed to consist of finely powdered lunar surface material shot out in long jets by meteorite impact. It is not hard to reconstruct, roughly at least, what happens when a denizen of interplanetary space crashes into the moon. Its speed may be as great as 50 miles per second, but even five miles per second gives it many times the energy of an equal quantity of exploding TNT. It penetrates a little way below the surface and turns into a mass of hot, highly compressed gas that expands irresistibly, sends out a shattering shock wave and tosses debris far and wide. Great blocks of moon-rock pile up on the crater rim, and incandescent jets of fast-moving dust and rock fragments shoot out in all directions. Those that soar sharply upward fall back to form the bright halos outside the rims, while those that shoot outward form the long rays. Both halos and rays are peppered with secondary craters





where heavy pieces of ejected material strike the surface and dig holes of their own.

It is likely that all the large craters on the moon, including the most ancient ones, were typical ray craters when they were first made, but with the slow passage of millions or billions of years they grew dim and obscure. Later impacts tossed dirt and debris over them or blasted gaps in their rims. A gradual darkening process that affects the entire lunar surface erased their bright rays and halos.

After the early formative period, so goes the best-established theory, the cratering process continued at a slower pace. Small meteorites dug their small craters, and every few million years a more violent impact blasted a crater that looked at first much as Copernicus does now.

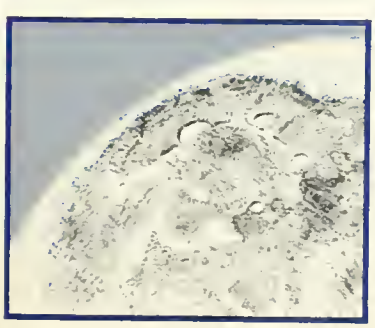
When the moon shook

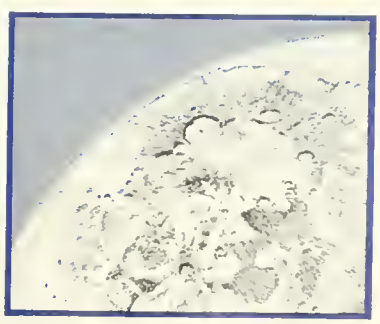
Then came the biggest of all. A massive body, perhaps an asteroid 100 miles in diameter, crashed into the moon north of the center of the present Mare Imbrium. The exact place where it hit is the point of intersection of the many radial valleys gouged by high-speed missiles from the great ensuing explosion. The Imbrian Event, as lunar experts call it, did much more than blast a crater. It must have shaken the entire moon and cracked its exterior.

Striking proofs of the Imbrian Event's enormous effect are the circular rings of mountains, some of them 20,000 feet high, that surround the impact point. These rings are more than 1,000 miles in diameter and are believed to have been formed by shock waves that traveled through the moon-rock and froze in the places where they are seen today. A rough terrestrial equivalent of the Imbrian Event would be an explosion that dug the Gulf of Mexico and raised most of the Rocky Mountains in the same few awesome minutes.

When freshly blasted, the Imbrium crater may have been more than 100 miles deep, but before long material rising from below partially filled it while the steep sides slumped toward the center. Even in this collapsed condition, it must then have been the moon's most conspicuous feature, a vast pit nearly 500 miles in diameter walled by a circular rim higher than any earthly mountains.

It is natural to ask why the moon should have suffered so many blows from space while the earth, probably its close companion for several billion years, seems to have escaped. The answer is that the earth did not escape; it merely covered most of its scars. As soon as scientists began to search seriously for impact craters on the earth, they found plenty of them. The famous Canyon Diablo crater in Arizona is only the most obvious and best preserved. Maps and aerial photographs have led the searchers to many other intriguing circular formations. In the very old





rocks exposed in Canada, for example, several large, almost perfectly circular lakes have been identified. Their features can be explained only as the result of meteorite impacts. Similar structures exist in many other parts of the earth.

The great scars left by meteorites

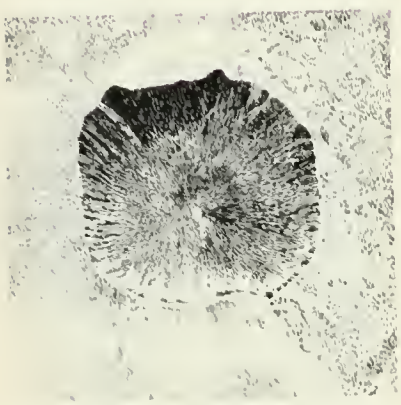
Drilling shows that these "astroblemes" (star-scars) usually contain the broken rubble that is to be expected in a meteorite crater. They are often surrounded by bedrock full of cone-shaped fractures made by the shock wave. There is seldom any trace of the meteorite itself, but this is not surprising. Unless it hits at unusually low speed, a meteorite will vaporize and spurt out of the crater as gas.

The biggest structure on earth that is suspected of being part of an astrobleme is near the Nastapoka Island chain on the eastern shore of Hudson Bay. These islands form a beautifully circular arc with its center of curvature out in the bay itself. If they are segments of an ancient rim, the crater must have been 275 miles in diameter, bigger than all but a very few craters on the moon. Not far away, the curving shores of the Gulf of St. Lawrence outline a somewhat smaller circle.

After the Imbrian Event the next stage in the moon's evolution was the development of the maria, the great level plains that are the moon's most conspicuous feature. This time the changes were caused by influence from within the moon, rather than from outside in space.

The maria are widely believed to be fields of lava that flowed through the surface, although the origin of the lava is still in doubt. Like the earth, the moon is thought to have originally formed as a fairly cool, solid body, and it apparently stayed solid long after radioactivity had heated the earth and melted much of its interior. Some experts believe that most of the moon's interior never got hot enough to soften but that parts near the surface did. One conjecture is that large impacts such as the Imbrian Event filled the brittle moon with fractures. When zones of the interior were melted by radioactivity and the heat produced by meteorite impacts, the lava that was formed came to the surface through the cracks. It may have flooded out at different times, filling low areas such as Oceanus Procellarum and turning the Imbrian depression into Mare Imbrium. Mountain ridges were no barrier for the lava, which moved underground as well as on the surface. In this way it could have penetrated many craters, large and small, turning the larger ones into flat, circular plains such as Mare Crisium and Mare Nectaris. Inside some craters, such as Wargentin, pressure seems to have forced the lava to high levels, above the level of the surface outside the craters.

Not all experts accept the lava theory. A minority insists that the moon has always been solid inside and that some other explanation must be found for the maria. One possibility is that large amounts of water or some other fluid gushed out of the moon, carried suspended material into low places and then evaporated. Another is that great clouds



THE CANYON DIABLO CRATER in Arizona, three quarters of a mile wide, was the first on earth to be positively identified as an astrobleme—a scar left by a giant meteorite. The clinching evidence was the discovery in 1960 that the crater contained coesite, a form of silica created by millions of pounds of force. Only the impact of a large object, believed to be a meteorite that landed about 25,000 years ago, could have produced such force

of gassy dust, like terrestrial volcanic ash-flows, may have deposited dry material in the low places. Pictures taken by U.S. Orbiter spacecraft circling around the moon show what look like meandering river channels that may have carried flows of ash or water a long time ago. The lava theory is supported, on the other hand, by instruments on both U.S. and Russian spacecraft. They found that in chemical composition the surface material of the maria is very like basalt, the most typical kind of rock in earthly lava flows.

Whatever the mare material may be, it soon became solid, conforming with remarkable accuracy to the moon's general shape. The period of mare formation is loosely set at three billion years ago, and it did not continue for long. After it was over, the moon resumed its routine existence, steadily pitted by small meteorites and occasionally shaken to its center by a big one, but none big enough to produce another Mare Imbrium.

Although the principal evidence for volcanism on the moon is material that fills the maria, there are other signs of it too. Scattered irregularly over the lunar surface are small, low-rimmed craters surrounded by very dark halos. They are probably vents through which gases carried material that blackened the nearby surface. There are also small craters arranged in rows, and these too are believed to be volcanic. They presumably trace a crack that released high-pressure gas deep in the moon's interior.

The mystery of the darkness

One of the most stubborn riddles presented by the moon is its surface structure and composition. For one thing, the lunar surface is surprisingly dark in color. The moon looks bright when it floats majestically across a clear night sky, but only because it has no competition. Actually its maria are about as dark as freshly washed blackboards. Other parts of the moon are somewhat lighter, but even the brightest rays and highlands might look as dark as blacktop roads if they were brought to the earth. As astronomers put it, the full moon's "visual albedo" is 0.073, which means that it reflects only 7.3 per cent of the visible light that hits it. By comparison, the earth is five times as reflective and cloud-covered Venus 10 times as reflective.

The appearance of the lunar surface also changes in a peculiar way: its brightness increases sharply when sunlight falls on it from the direction of the observer. The full moon, which is seen when the sun is almost behind the earth, is not merely twice as bright as the half-moon. It is nine times as bright, and the light reflected from it doubles during the last two days before it is full.

The only kind of surface that would behave this way is one that is riddled with cavities. The cavities show as black shadows when sunlit from one side, but disappear when sunlight comes from the observer's direction to illuminate their bottoms. No common powder

ASTROBLEMES in North America located on the map above, are the scars of meteorite bombardments that have pockmarked the earth and moon over the past four or five billion years. The arrow indicates the Canyon Diablo crater *(opposite)*. The huge circular formation at the lower end of Hudson Bay, 275 miles in diameter, is the world's largest identified astrobleme. However, mountain-building and water erosion have obliterated most of the earth's astroblemes, while erosion on the moon has had less effect on lunar craters.

or granulated substance gives quite this effect. The natural material that most closely approaches the moon's reflecting properties is *Cladonia rangiferina*, a spongy lichen with many fine clefts, but no one thinks the moon is a field of lichen.

A surface of fairy castles

Many attempts have been made to put together a material that reflects light the way the moon does and that also might exist on the moon. The most convincing imitation is achieved in the laboratory by dropping dust particles one by one through a vacuum. Instead of piling up in a heap, as they would if they were dropped in air, the bits of dust stick together and build up into extraordinary structures that astronomers call "fairy castles." Some of them are only 10 per cent solid; the rest is empty space. Their cavities reflect sunlight much as the moon does.

Fairy castles could form on the moon since the only requirements are a vacuum and fine particles. If the moon had an atmosphere, the particles would be surrounded, as they are on the earth, by gas molecules that would prevent them from sticking together. But in a vacuum the crystalline materials of which such particles are made adhere to each other strongly by the atom-to-atom process called "vacuum welding."

HOSTILE MOON MEN, shown capturing an explorer from earth in this illustration from H. G Wells's 1901 novel, *First Men in the Moon*, fascinated early generations of science fiction readers. Called Selenites, they were intelligent, spindly-limbed creatures who lived in underground lunar caves, breathed oxygen in a rarefied atmosphere and ate fungi. Though such beings seemed plausible when the novel was published, astronomers now realize that, since the moon lacks an atmosphere and surface water, the chances that it supports life are very slim.

The fairy castles built up in a laboratory are very small, but similar structures on the moon, which may have been building for billions of years, could be larger. They could still be soft and light because there is no wind or rain on the moon to destroy them. Closeup pictures by U.S. and Soviet moon-landing craft do not really conflict with the fairy-castle hypothesis. They show that the lunar surface material, in some places at least, behaves remarkably like moist garden soil, not like loose dust or sand. When the supports of spacecraft have moved, they have left sharp imprints, proving that the moon soil clings together and that it is made of very fine particles. The U.S. spacecraft Surveyor III, which landed on the moon in 1967, carried a small scoop to dig into the soil. Pictures taken of this operation showed that the disturbed soil forms crumbs. The particles may be stuck together by vacuum welding, but this cannot be confirmed until pictures with much finer detail have been taken. Another interesting and still unexplained fact discovered by Surveyor III's digging was that the material a few inches below the surface is even darker than the surface itself.

The fairy castles, or something very similar like frothy cooled lava, would offer an explanation for another surprising fact about the moon's surface: the way it cools off almost instantly. In full vertical sunlight it is as hot as boiling water on earth (212° F.), but when the shadow of the earth creeps across it during a lunar eclipse its temperature drops rapidly, reaching −150° F. in as little as an hour and a half.

The most acceptable explanation of this odd behavior is that the surface is covered with a material whose low density makes it an extremely

good heat insulator. Only a thin layer would be involved in the temperature change. This layer would give up its own heat quickly, becoming very cold as soon as the sunlight leaves it, and its insulating power would prevent additional heat from rising from the underlying layers.

Radio astronomy strongly supports this view. The moon emits weak radio waves that can be used to tell the temperature of material below the actual surface. They show that a few inches down the temperature changes very little when an eclipse cuts off the sun's warmth. At a somewhat greater depth it does not vary at all. Wrapped in its insulating blanket, the moon's subsurface stays at −40° F. throughout the glaring heat of its two-week day and the deadly cold of its two-week night. How the insulating blanket of fairy castles was formed is still a matter of some conjecture. The most widely accepted view is that dust was produced by the meteorites of all sizes that continually strike the moon. Even the smallest can splash out many times its own weight in dust particles, some of which may stick together as they fall to the surface. The fairy-castle layer cannot be deep, and whatever underlies it must become more solid with increasing depth, as recent radar evidence suggests. It may be full of cavities, however, since the moon's weak gravitation will not pack dust as tightly as the earth's would.

But if the moon's surface is loosely packed, how can it be so dark? On the earth finely divided materials are apt to be light-colored. The most likely answer is that the airless surface is bombarded by high-speed protons (hydrogen nuclei) shot out of the sun. Experiments have shown that bombardment by protons slowly darkens most kinds of dust by damaging the structure of their crystals so that they absorb light.

Tiny craters

The spectacular pictures taken by spacecraft showed many new details on the moon's surface. Some of them were expected, such as impact craters of all sizes down to a small fraction of an inch in diameter. Presumably, the moon has billions of these miniature craters blasted by micrometeorites. Some of the spacecraft pictures give enlarged views of one of the bright rays from the crater Tycho. As was expected, they show small secondary craters dug by sizable chunks of rock thrown out of Tycho along with the powdery ray material. What was not expected is the relative rareness of loose rocks on the surface surrounding the crater, although other parts of the moon are thickly strewn with rocks. Tycho is a very young crater, so rocks thrown out of it would not have time to be covered by slowly accumulating dust. Perhaps a better explanation is that the lunar surface is so yielding in places that rocks from Tycho plunged deeply into it and disappeared.

Ranger IX, one of the earliest successful lunar spacecraft, provided scientists with still another surprise by revealing the slump pits that

dot the surface in many places. They are on mare material, and they look superficially like small craters. But they cannot be craters because they lack raised rims of ejected debris, and their cross sections resemble wineglasses rather than the bowl shapes of ordinary impact craters. They seem to have been formed by loose surface material falling or draining into underground cavities. Many places on the earth have similar slump pits where the ground has collapsed into limestone caves just below the surface.

The moon's slump pits suggest that much of the mare material has large, weak-roofed cavities in it. How they got there is not known, but an obvious possibility is that they are gas bubbles in solidified lava, perhaps permitted to grow to great size by the moon's surface vacuum and low gravity. When the bubbly surface was covered with debris from later meteorite impacts, some of the weakest bubbles collapsed under the weight, allowing loose material to sink, leaving slump pits on the surface and releasing puffs of gas to space.

Caves for an Astronaut base

Astronauts landing on the moon will be prudent to avoid such treacherous places, but the caves may prove extremely valuable for sheltering lunar explorers. Even a few feet underground the caves will be cooler than the moon's surface by day, warmer by night. Large caves with strong walls could perhaps be sealed, filled with breathable gas and used as long-term quarters. There the explorers would be well protected from micrometeorites, solar protons and other inclemencies of the lunar outdoors.

Caves on the moon were foreseen by H. G. Wells. His novel *The First Men in the Moon,* published in 1901, is not one of his finest works of science fiction, and the intelligent "Selenites" he depicted inhabiting the caves are not to be taken seriously. But if earthlings do try to colonize the moon, they will certainly search, like the Wellsian Selenites, for caves or crevices leading below its inhospitable surface. There they will hope to find not only shelter but water, the essential medium of earth-born life.

The moon is known to be waterless only on the surface. Astronomers seriously believe that about 100 feet below may lie a layer of porous material saturated with ice like the permafrost that is common in the earth's Arctic regions. This frozen layer may have been formed by water vapor, outgassed from the moon's interior and turned to ice when it reached the extremely cold regions just below the surface. Water in liquid form may be found a little deeper down and nearer the warm interior of the moon. Lunar colonists would use this treasure, to them more precious than diamonds, not only for drinking, but also as a raw material from which to extract oxygen for breathing, and perhaps for use as a rocket propellant.

Liquid water trapped under a seal of permafrost is about the only possible place where indigenous life might be found on the moon. There is

little chance that life could develop on the barren surface under violent bombardment from the sun, but subsurface environments offer a faint possibility. If underground water does exist, it probably contains many materials, perhaps including carbon compounds that were carried up with the water vapor from the deep interior. Life may have evolved somehow in this ancient soup as it did in the earth's oceans, but underground, in the absence of sunlight, the available energy for life is sparse. Life on the moon is not at all likely, but no prudent scientist would exclude it entirely.

Even if it contains no water, the material just below the surface is expected to be of great scientific interest. For at least two billion years most of it has lain almost undisturbed, and parts may be found that have changed hardly at all for four billion years or more. Such well-preserved ancient relics are extremely rare on the earth, whose surface is usually altered almost as soon as it is formed. When the first samples of subsurface lunar materials are brought back to the earth, they will create enormous excitement and will be studied intensively with all the methods and instruments known to science.

Ancient samples from the moon

No one can guess in advance what secrets the samples will reveal. Analysis may determine the age of the moon and tell whether it was formed in the same part of the solar system as the earth. The samples may have a layered structure that marks the passage of time like the rings in tree trunks; it may be possible to tell from these how conditions in space have varied since the youth of the moon. The layers may point, for instance, to periods when dust was unusually plentiful in the solar system, dimming the light from the sun, as has been suggested in theories of the earth's recurrent ice ages.

Many surprises are possible. The moon's surface may contain strange, unstable chemical compounds that could not exist for an instant on the earth but have been preserved on the moon by vacuum and cold. The chronicle of the lunar surface may even reach back to the birth of the solar system.

It is not unlikely that organic matter of some sort (but not necessarily formed by living organisms) will be found in samples of lunar material. If so, it might provide clues to the origin of terrestrial life. If it shows traces of once-living organisms, they may have come from the earth, and have been tossed to the moon by an ancient asteroid impact. Hardy spores may be found that have been kept dimly alive below the moon's permafrost layer. Perhaps they can be revived to show what life was like on the earth billions of years ago. Or perhaps they originated in water that has been retained beneath the moon's surface and represent a kind of life never known on earth.

None of these eventualities is likely, but no possibility, however remote, will be neglected when the first ancient sample of the moon is brought down to earth.

RUSSIA'S LUNA IX, the first craft to make a successful soft landing on the moon, is shown in this artist's conception. Only two feet high and weighing 220 pounds, the capsule transmitted a series of remarkable photographs back to earth. Luna IX also dispelled fears that the moon is blanketed by a layer of dust thick enough to engulf exploratory vehicles.

The Earth's Companion

The closest and best-known object in the sky is the earth's constant companion, the moon. This satellite affords many important clues about the nature of the planets. In fact, the moon itself is sometimes referred to as a planet; it differs from true planets only in its orbit, which carries it around the planet earth, and it probably bears a closer resemblance to certain planets than some planets do to one another. Thus, Mercury and Mars, which have little atmosphere, may be more similar in composition and structure to the airless moon than to the gaseous planets Jupiter and Saturn.

Many facts are known about the moon: its surface *(right)* is a ravaged wasteland; its gravitational pull is so weak that a shell fired from it would travel halfway around its circumference before falling back to the surface; though the moon lights the night on earth, it actually reflects light poorly. But real investigation of the moon's mysteries has scarcely begun. Not until the first man sets foot on it will science understand much about its origin, composition and geology. And the first lunar explorations may also provide some of the answers to the nature and origins of the planets.

FEATURES OF THE HALF-MOON

The dark "seas" and the bright craters of the half-moon stand out in sharp contrast in this photograph, which was taken by the 36-inch telescope at the Lick Observatory in California. The crater nearest the center of the picture is Copernicus, which is as large as Puerto Rico. The smooth, dark area above Copernicus is one of the moon's largest "seas," Mare Imbrium, the Sea of Rains.

Waterless "Seas" of the Moon

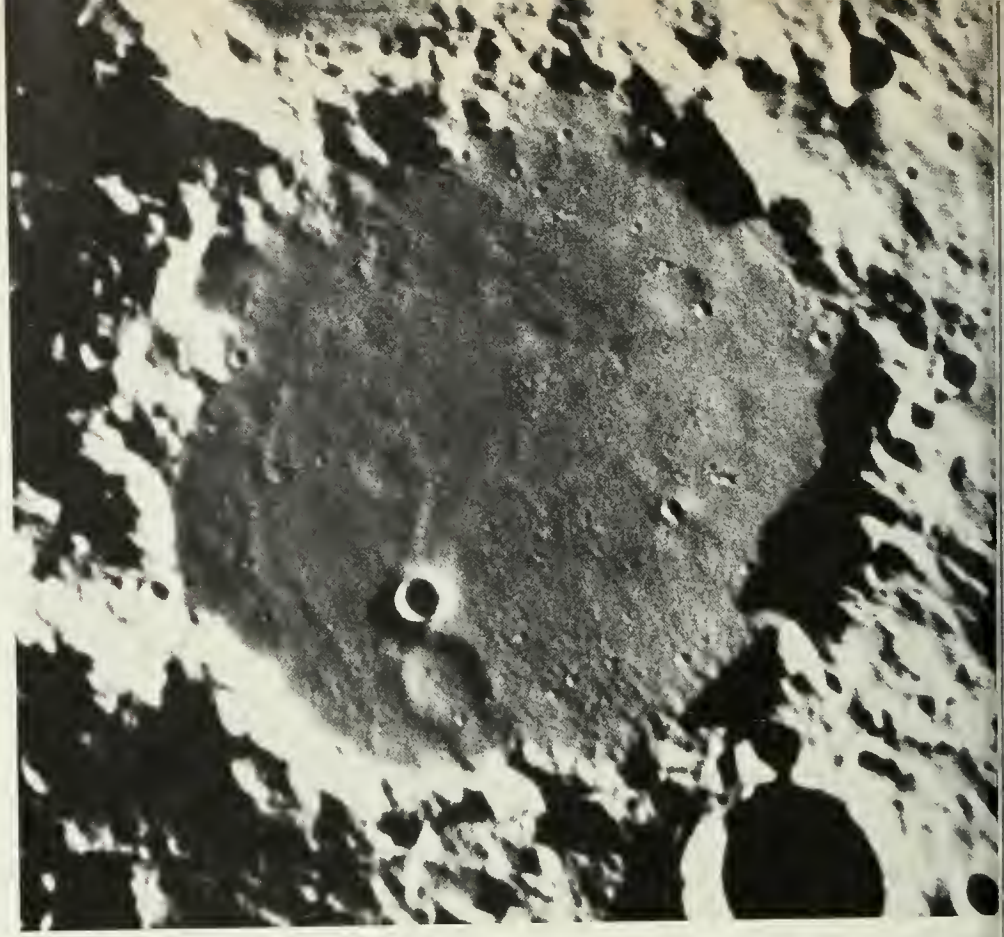
To 17th Century astronomers peering through their telescopes, the dark, smooth areas on the surface of the moon could be only one thing: they called them *maria*, the Latin word for "seas." The term could not have been more inaccurate: the moon has no atmosphere, and consequently no surface water or rain. Maria, which are visible to us as the features of the man in the moon, are now believed to be depressions on the lunar surface that have filled up with lava, meteoritic dust or volcanic ash. They occupy about half the visible surface of the moon; the largest, Oceanus Procellarum, or the Ocean of Storms, where the Soviet spacecraft Luna IX landed with its instruments in February 1966, covers more than two million square miles, the area of the Caribbean and the Mediterranean Seas together.

Maria are smooth only by comparison with the rest of the moon's areas. Land-swells rise from their surfaces, and small craters and twisted ridges are common within their confines. The maria may be unique to the moon; nothing exactly like them has been observed on the planets—although Mercury shows some intriguing dark spots that may prove to be the first known planetary "seas."

THE CRESCENT'S BLACK EYE

The dull, dark circle of Mare Crisium, the Sea of Crises, stands out like the great eye of a Cyclops in a four-day crescent moon. Deepest of the moon's maria, Mare Crisium is as large as all the Great Lakes, and is readily visible to the naked eye. Its circular shape (distorted here by perspective) as well as the mountains that surround its shores and its dark surface are characteristic features of the maria of the moon.

The floor of Mare Imbrium, a lusterless lunar sea some 750 miles wide, is pocked with craterlets, probably caused by meteorites



AN ANCIENT CRATER
Ptolemaeus, a lunar crater about 90 miles wide, is believed to have been excavated by a giant meteorite more than three billion years ago. It later was filled with the same kind of material that the maria contain. The small holes in its floor may be of meteoritic and volcanic origin.

A YOUTHFUL CRATER
Copernicus *(below)*, a circular plain about 60 miles wide, is a relatively recent meteoritic crater, containing no material like that found in Ptolemaeus. The 12,000-foot-high walls around its rim and the peaks at its center were formed by the giant impacting meteorite that dug the crater, probably less than 10 million years ago

The Vast Pits of a Lunar Panorama

Seen through a telescope, the moon is a battered, forbidding place. Its surface is pocked with millions of craters, dug by meteoritic bombardment. The earth has been subjected to similar attack, but wind and water erosion have all but removed its traces. Nothing yet seen in the solar system is quite so stark and desolate as the moon.

Telescopic photographs like those on these pages make the moon's craters seem small. But the larger craters actually are so big and the curvature of the moon's surface is so great that if an Astronaut were to land in the center of a large crater its ramparts would be beyond his horizon.

THE MOON'S BADLANDS

The southern highlands of the moon, its most heavily cratered area, cover a tenth of its visible surface. Astronomers believe this vast field of overlapping craters is the "oldest" part of the moon. In other parts of the lunar landscape, the formation of maria has destroyed many of the older surface features, but here the original bombarded surface of the moon can be seen clearly

Rills, Rays and a Great Wall

The riotous hodgepodge of the surface of the moon includes many features unlike anything observed on earth: among these are the moon's distinctive rills, or clefts, a great wall formed by the fracturing of the lunar surface, and a series of dazzling rays.

The rays are evident only when the moon is full; at such times, long white streaks are visible radiating from many of the lunar craters. Some rays are as long as 1,500 miles, crossing over mountains, seas and craters. Astronomers have long debated the nature of these rays. In past years some scientists suggested that they were fields of ice crystals, or salt deposits dried to white intensity by the heat of the sun. Today they are believed to be powdered surface material splattered out of young lunar craters by the meteorites that dug them millions of years ago. Eventually protons, or charged particles from the sun, will darken them into obscurity, like the older rayless craters.

A LONG CRACK
The rill Ariadaeus, a relatively young feature of the moon, was probably caused by a cracking of its surface. Rills, which have no exact geologic counterparts on earth, occur generally along the edges of the maria

A HUGE CLIFF
The Straight Wall, the only feature of its kind on the moonscape, is a cliff like mass forced above the lunar surface by internal pressure. Most slopes on the moon are gradual, but this 1,000 foot wall has a 41° slope

A NETWORK OF RAYS
The most brilliant and extensive system of rays on the moon centers around the crater Tycho. Because this ray network lies on top of other lunar features and has not been disturbed, it is believed to be a relatively new moon feature

THE MOON'S HIDDEN SIDE

The side of the moon never seen from earth is shown in this picture taken by Lunar Orbiter III. The spot near the center, filled with dark material, is the 150-mile-wide crater Tsiolkovsky

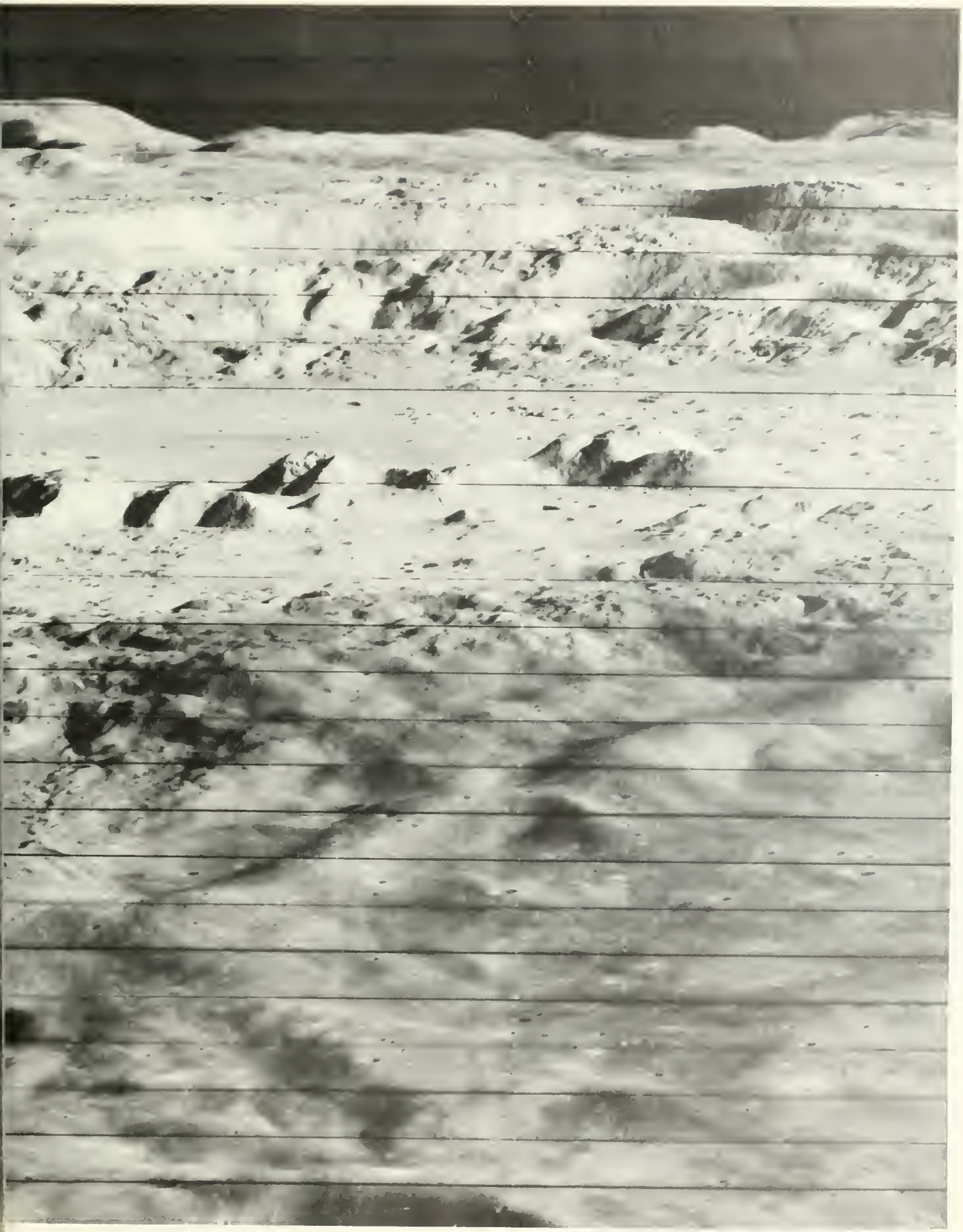
Close Looks at the Lunar Surface

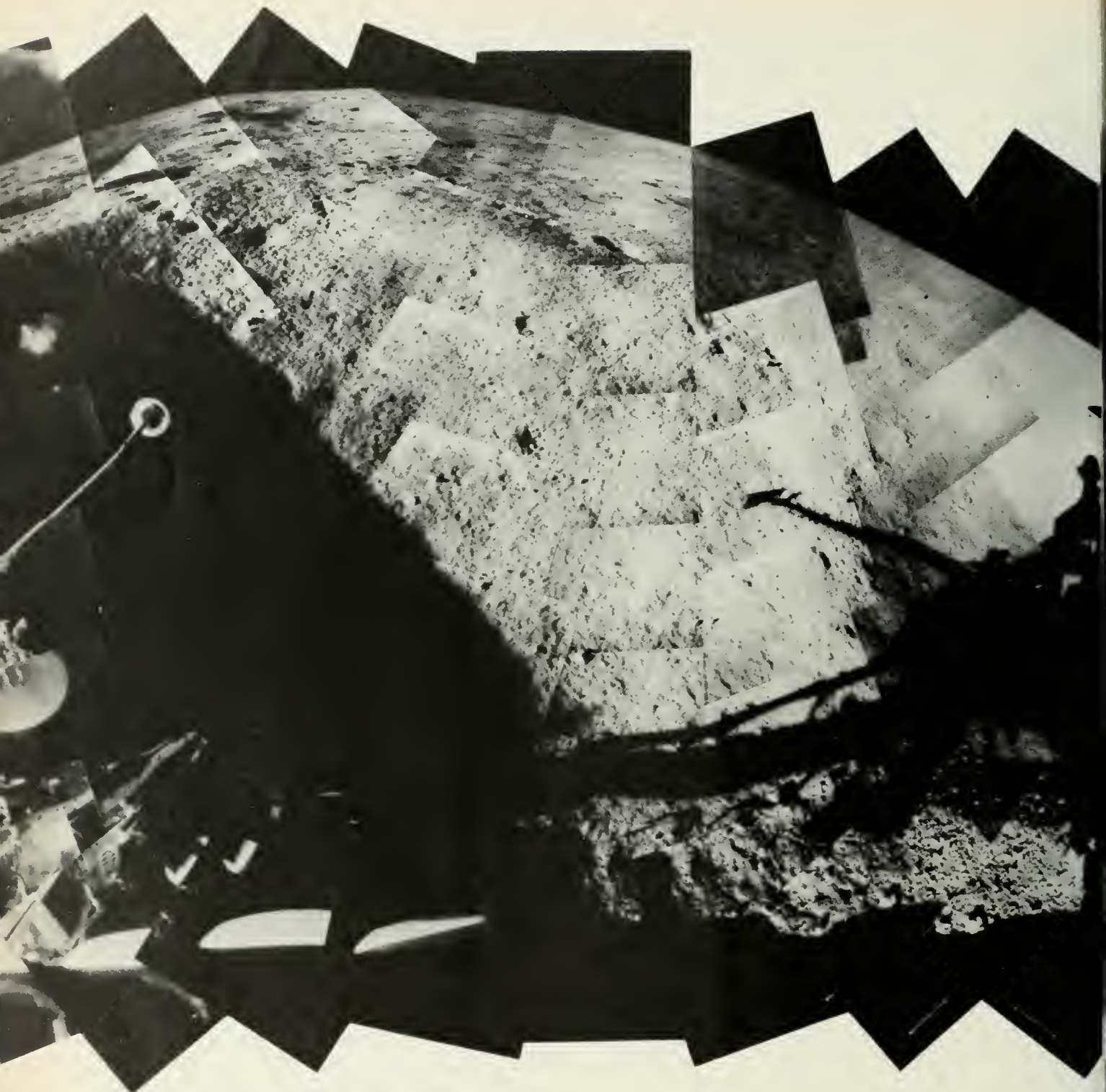
During recent years U.S. and Russian space vehicles have provided the first closeup pictures of the moon. By 1959 the Soviet Luna III approached within 5,000 miles of the lunar surface—a sensational achievment at the time—and took the first pictures of the moon's hidden side. By 1966 the American Lunar Orbiter II was able to snap the view at right from a distance of only 29 miles above the moon. It sent back to earth a most spectacular scene: a clear and starkly beautiful view of the rugged, desolate crater Copernicus.

Even more than clearly detailed pictures of familiar features could be furnished by the moon probes. As they soared near the moon they were able to solve one of its most mysterious puzzles: what lay on the far side? It had never been seen because the moon rotates roughly only once as it completes each full revolution, always keeping approximately the same face to the earth while hiding its other side. But the Soviet Zond III and later the U.S. Lunar Orbiters traveled around the "back," and sent to earth, some 240,000 miles away, detailed coverage of more than 95 per cent of the hidden side of the moon.

THE LUNAR LANDSCAPE

Scanning an area of over 14,000 square miles, the cameras of Lunar Orbiter III revealed details of domes around the crater Marius, located in the right-hand corner of the above picture, the domes supported the belief that volcanic activity has played an important role in shaping the moon's surface. The picture at the right shows a portion of the floor of the crater Copernicus, which is 60 miles long and two miles deep. Rising from the huge depression are hills about 1,000 feet high. At the bottom of the picture is the crater Fauth.





Details from Robots on the Moon

When the first man to land on the moon looks around, he will see a surface of rocks and fine particles. Even the kinds of rocks he will find are already known, long in advance of the first human explorations, because scientists have observed them and analyzed them by remote control. Robot spacecraft have landed gently

on the moon, dug into its surface, tested the material chemically and magnetically, and televised closeup photographs. The clear picture above is a mosaic of views taken by one of these craft, Surveyor V, when it landed in Mare Tranquillitatis (Sea of Tranquillity) on September 11, 1967. The camera swung completely around to reveal not only the sharply sandy surface of the moon, but also to pick up parts of the spacecraft *(far left and far right)* and its shadow *(center)*, and the moon's horizon, which appears against the blackness of space in an unnatural curve because the camera was tilted.

The findings of the American and Russian probes suggest that the moon's surface, like the earth's, is largely made of basalt, a dark volcanic rock. One robot had a magnet that sliced through the soil and attracted it, showing that it contained iron. These closeup observations promise a surface similar to earth's —sturdy enough for men to land on.

Vehicles for Moon-roaming

The first men to explore the moon will face many problems. Walking and vehicular movement will be difficult. Because there is no atmosphere, the sun's ultraviolet rays are blinding and a major meteorite shower can be as deadly as machine-gun fire.

To cope with some of these problems in advance, members of the U.S. Geological Survey at Flagstaff are testing special vehicles and developing techniques for gathering samples of the surface. But the worst problem of all remains insoluble: until men actually visit the moon, no one knows what surprises it has in store.

AN AID IN WALKING
A device like the one used by children learning to walk is tested at Flagstaff as an aid to an Astronaut trying to negotiate the treacherous surface of the moon. Hanging from its bars are bags for rock samples. The Astronaut's staff contains a still camera and measuring devices.

A ROLLING LABORATORY
A geologic lunar laboratory 12 feet high lumbers across a rock ridge in Arizona. Among the special problems posed by lunar travel is that of lubrication: the usual lubricants do not function in a vacuum such as exists on the moon.

5

The Mystery of the Clouded Body

A 4,000-year-old Babylonian tablet, found in the 19th Century, records Venus' movements.

When the first telescopes were turned on the planet Venus in the early 17th Century, there was good reason to hope for startling discoveries. Venus is the third brightest object in the sky, exceeded only by the sun and moon, and of all the planets it comes nearest the earth. If it were really a world like the earth, as astronomers of the time had begun to believe, it ought to show many wonders, perhaps "seas" and "continents" like the moon's, perhaps even inhabitants.

Venus showed nothing of the sort. It is a sad disappointment to the visual observer. It passes through phases like the moon's because its orbit between the earth and sun makes different amounts of its illuminated hemisphere visible at different times, but the phases are about the only interesting thing that can be seen. Venus has no satellites like Jupiter, no rings like Saturn, no ice caps like Mars. All it shows to the eye at the telescope is a bright, slightly yellowish cloud deck that effectively hides its surface. Astronomers soon tired of staring at this featureless wrapping, and most of them abandoned Venus as not worth further effort.

The cloud deck is still a barrier to observation with optical telescopes, but Venus is no longer a hopeless enigma. Since 1956 an amazing amount has been learned about its atmosphere and clouds, and even about the climate and topography of its hidden surface. Delicate new instruments were needed to extract faint clues from the cloud-shrouded planet, and subtle reasoning processes interpreted their meanings. The history of the campaign reads like a detective story, and its triumph is one of the great successes of modern astronomy.

Centuries of visual study had given the Venus detectives precious little to build on. The orbit of Venus (about 67 million miles from the sun) was easy to figure from repeated observations, but its mass was more elusive. The mass of a planet is calculated from its gravitational effect. The handiest method is to measure the distance and orbital period of a satellite, then insert these two figures in the proper equation derived from Newton's law of gravitation, which gives the mass of the parent body. But Venus has no satellite, so its mass had to be calculated from the effect of its gravitation on other bodies. The planet's size gave trouble too. Since nothing could be seen except the cloud deck—whose altitude was unknown—the diameter of the planet itself could not be measured with confidence.

From properties of the atmosphere the height of the clouds has been estimated, permitting the diameter to be determined with some accuracy. Venus turns out to be almost a twin of the earth so far as size is concerned. Its diameter is slightly less than the earth's at the equator (about 7,560 versus 7,926 miles). Its mass is 81.4 per cent of the earth's, which makes its density less. Besides the unbroken clouds, Venus has an atmosphere so substantial that it is obvious even to visual observers. When Venus is passing directly between the earth and the sun, its illuminated face becomes a slender, diminishing crescent, and the tips of the crescent can be seen to extend until they become a faint ring of light

enclosing the whole planet. This is the work of the atmosphere above the clouds, scattering sunlight around the planet.

Most other observations with ordinary telescopes proved of little help to the Venus detectives. Some observers saw faint shadings on the clouds; others saw none. Since there are no permanent markings to watch as they turn with the planet, the rotation of Venus could not be measured, and the positions of the poles and equator remained unknown.

The soda-water sea

The first big break in the case of the cloud-covered planet came in 1932, when spectroscopy found evidence of large amounts of carbon dioxide in its atmosphere. Improved hypotheses were constructed from this single clue, including the intriguing concept of a planet covered with a sea of soda water or, alternatively, petroleum. But no firm information was available about the hidden surface until the new techniques of radio astronomy found ways to measure the temperature under the clouds.

The temperature of the cloud deck itself had already been determined in two independent ways. Venus is nearer the sun than the earth is, and it receives about twice as much solar radiation, but its clouds are so bright that they reflect about 70 per cent of the sunlight back into space. Starting with this fact and assuming that the rest of the sunlight is absorbed by the clouds, astronomers are able to make a theoretical estimate of the temperature of the clouds, which comes out as −40° F. Direct measurements by infrared light show that the clouds are actually very close to this theoretical temperature. If they contain water at this temperature, it must be in the form of ice crystals.

The two estimates of cloud-deck temperature confirmed each other nicely, but they did not cast any light on conditions below the clouds. Then, in 1956, radio astronomers detected three-centimeter (about one inch) microwaves coming from Venus. This wavelength is absorbed by very few materials, so it is presumably able to pass through both the atmosphere and the clouds. The three-centimeter waves seem to originate in the hidden surface. Since the intensity of radiation can be used to tell the temperature of its source, calculations quickly showed that the surface of Venus, as revealed by the microwaves, must be at least as hot as 600° F. Later observations showed even higher temperatures. In some places the surface must get hot enough to glow a deep, dull red.

Here was a startling picture: a red-hot planet wrapped in clouds of ice! The Venus detectives took a long breath and began to think of the planet as having a very deep atmosphere with very hot lower levels above a glowing surface. Then some scientists had an alternative idea. Perhaps, they speculated, the microwaves do not come from the surface; they may come from the ionosphere of Venus, many miles above the cloud deck. At this level, solar ultraviolet light and high-energy solar particles have detached electrons from gas atoms, creating charged particles called ions. Such a gas is called ionized, and it gives off microwaves

when its electrically charged particles are attracted toward or repelled by each other. If the ionosphere of Venus could be shown to be about a thousand times richer in ions than the earth's, the microwave emission at three centimeters and longer might come from it, not from any hot surface far below.

The red-hot surface, then, might be an illusion. A further calculation of temperature could be made from microwaves very much shorter, a few tenths of an inch long, that also come from Venus. This calculation assumes that they arise from the lower atmosphere and can pass through the ionosphere. The temperature of the lower atmosphere deduced in this way is about 170° F., and the actual surface was thought to be close to the same temperature. It would be uncomfortably hot by the earth's climatic standards but not wholly impossible for the kind of life that has evolved on the earth. Some parts of Venus, especially the poles, might be considerably cooler and quite hospitable to earthly kinds of life.

Human wishful thinking was all on the side of this "cool" concept of the planet. Generations of dreamers had pictured Venus as having a reasonable climate and many fascinating plants and animals under its bright clouds, and few astronomers wanted to believe that the earth's nearest planetary neighbor might actually be hot enough on its surface to destroy all living things, as if they were bacon charred black in an unwatched frying pan.

And then in 1962 the U.S. spacecraft Mariner II completed a spectacular 109-day voyage to Venus and observed the planet from the distance of 21,600 miles. On board were instruments sensitive to microwaves and infrared light, and the data they gathered during the flyby were sent by radio to the earth, 37 million miles away.

The hot and cool Venus

For the purpose of deciding between the hot and cool concepts of Venus, the key instrument was a detector tuned to pick up waves that could originate in the planet's ionosphere. The detector measured these waves as they were received from two directions—from a direct path to the bottom of the atmosphere, and from an oblique path through the other part of the atmosphere. The oblique path, being longer, included more of the ionosphere layer; thus, if Venus had a dense ionosphere, as the cool hypothesis demanded, the oblique path would furnish a greater amount of the waves than the direct path. Just the opposite was observed. Mariner II reported that as it scanned Venus it received more waves directly than obliquely. This result implies that Venus does not have an ionosphere sufficiently dense to be the source of its microwave emission. But such a microwave-emitting layer is a necessary part of the cool view of the planet and its absence means that Venus does not have a cool surface under the clouds. Most of the planet's surface is almost red-hot. A different set of instruments on Mariner V supported this conclusion in 1967 and in the same year, the Soviet

spacecraft Venera IV sent into the atmosphere of Venus a capsule that reported temperature by radio. There is disagreement about whether the capsule reached the solid surface with its instruments still working, but in any case its findings indicated that the surface temperature could not be much lower than had already been determined from the faraway earth.

With this point settled, the next task of the Venus detectives was to explain why the surface is so hot. The only plausible source of the heat is sunlight, and the most likely mechanism for concentrating it is the "greenhouse effect," which operates to a lesser extent in the atmosphere of the earth.

The greenhouse effect takes its name from the familiar florist's greenhouse, a handy device to trap solar energy and thereby keep the temperature inside above that of the air outdoors. When sunlight passes through the glass roof, it mildly warms the plants and soil that it hits. They radiate some of this heat back, but since their temperature is relatively low, the radiation they emit toward the sky is long in wavelength. These long wavelengths do not easily pass through glass, but are blocked by it. Their heat energy cannot escape and so it makes the temperature rise inside the greenhouse.

A greenhouse in the sky

On Venus the role of the greenhouse glass could be played by the deep, dense atmosphere—if it could be shown to contain enough heat-stopping materials. No single substance in it has enough blocking effect to make the surface red-hot. Some of the infrared wavelengths that try to escape into space are blocked by the carbon dioxide that is known to exist in the atmosphere of Venus, but other wavelengths not stopped by carbon dioxide would carry heat away, like air leaking through broken panes in a greenhouse roof, unless they were stopped by something else.

Water vapor could do that—if it were really present on Venus. All early attempts to detect it, however, were utter failures. The main trouble was the water vapor in the earth's atmosphere, which tended to hide any clues to water that might be offered by spectra of the feeble sunlight reflected from Venus. The difficulty was finally sidestepped by attaching an infrared spectrometer to a balloon to carry it above most of the earth's water vapor. The experiment showed that the atmosphere of Venus does contain water vapor and the Soviet capsule reported just the right amount to trap additional heat and account for the planet's high surface temperature. The goodly amount of water in the atmosphere indicates that the tops of the clouds must be made of ice particles, not of dust or other solid matter.

At the subsolar point (the place where sunlight falls vertically), the temperature may rise to 1,300° F. Elsewhere, however, temperatures could be different, influenced by factors in addition to solar heat. Are there cooler polar regions? Do conditions change during the seasons,

or from day to night? Before such questions could be answered by theory, the Venus detectives had to find out how fast Venus rotates.

The most obvious way to determine rotation is to watch the surface markings moving across the face of a planet, but this did not work for Venus, whose clouds hide all the surface markings and have no lasting markings of their own. Equally fruitless were attempts to use spectroscopes and conventional telescopes to measure rotation by the so-called Doppler shift—which refers to the fact that waves of light reflected from an approaching body are shortened, while those reflected from a retreating body are lengthened. In each case the size of the shift in wavelength tells how fast the body is approaching or moving away. If light is reflected from the edge of a rotating sphere, its Doppler shift tells how fast the surface is moving toward or away from the observer, and therefore tells the sphere's speed of rotation.

Spectroscopic study of the Doppler shift works well with many stars and most planets, but although it was often tried on Venus, using the world's best optical telescopes, it never succeeded. Sunlight reflected from the edges of the planet's disk stubbornly refused to show any shift. All these negative results indicated that Venus rotated very slowly, if at all. Until recently the most common opinion was that it always kept the same face toward the sun, just as the moon keeps the same face toward the earth.

The first positive information about the rotation of Venus came in the early 1960s from the rapidly improving techniques of radar astronomy. When a beam of microwaves is turned on Venus, most of the echo that returns is reflected from a small area in the center of the planet where the surface is almost perpendicular to the incoming waves. Weaker echoes come from the edges of the planet, and their wavelengths, which can be measured very precisely, show small but distinct Doppler shifts —strong evidence that the edges of the planet move; Venus rotates.

The wrong-way planet

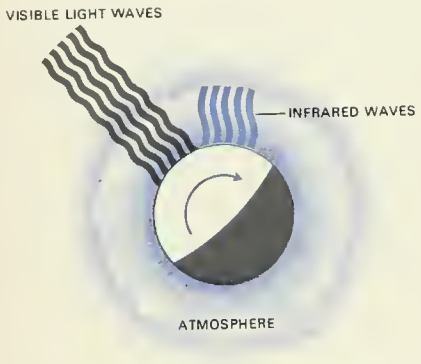
The story the microwaves told about Venus was exciting to all astronomers. With the exception of Uranus, all planets whose rotation is known have what is called "direct" rotation. This means that they rotate in the same direction in which they revolve in their orbits around the sun. Venus, however, is different. Radar astronomy proves that its rotation is "retrograde"; like a wheel spinning backward, it turns in the wrong direction. No one knows the reason for the planetary perversity, but astronomers welcome it as a new and fascinating mystery. Its solution might well cast some light on the way in which the solar system was formed.

Venus' retrograde rotation is very slow. It turns on its axis about once in 243 earth days. Since its orbit around the sun takes 224.7 days, the combination of the two motions makes sunrise take place on Venus at intervals of about 118 earth days.

Determination of the planet's rotation period was an important break

for the Venus detectives. It indicated to them that Venus should have notable changes of temperature during its long day. So it turned out. Careful analysis of radio waves, which are believed to come from just below the surface, shows that the surface on the dark night side may cool down by as much as 700° F. When the subsolar point is at 1,300° F., the temperature of the antisolar point—in the center of the dark hemisphere—is about 600° F. The polar regions may be even cooler, perhaps as cool as 400° F. This temperature is above the boiling point of water on the earth (212° F. at sea level). But since the atmospheric pressure on Venus is much greater, raising the boiling point, there is a bare possibility that water can exist as a liquid near the comparatively cool poles. It would not be much like the water in the earth's oceans. It would be more like the violent stuff confined in a power-plant boiler in full operation.

Without an actual "soft" landing on Venus, trying to determine what the surface is like under the unbroken clouds might seem hopeless. And yet the subtle techniques of the new radio astronomy have gathered a surprising amount of information by analyzing the lengths of waves emitted by the surface. The longer waves are believed to come from greater depths than the short ones, and they reveal that the deeper material has a more stable temperature, not heating as much by day or cooling as much at night. At a depth of about a yard, the temperature variation is already very small. This means that the surface material must be a very good heat insulator, better than nearly all solid rocks. Therefore, large areas of Venus must be covered with finely pulverized dust, which has about the right insulating properties.



THE GREENHOUSE EFFECT which warms the earth may similarly exist on Venus. The effect begins when short, visible light waves from the sun penetrate the atmosphere during the day. As the planet's surface absorbs them, it heats up and radiates long, infrared waves which are then trapped by the atmosphere and clouds, just as they would be by the glass walls of a greenhouse. If none of the infrared waves escaped, the surface temperature would increase indefinitely. But on earth enough of them do escape to maintain a balance with the incoming sunlight, stabilizing the temperature of the earth's surface at about 50°F. higher than it would be without the greenhouse effect.

Mountains on Venus

Radar astronomy has made the extraordinary discovery that mountain ranges and large craters, or something that looks very much like them, exist on the surface of Venus. These objects do not show themselves directly, like ships or airplanes on the scope of a military radar. Venus is so far away that any existing beam of radar waves spreads out so much that it cannot concentrate on a portion of the planet. The echo that comes back has been reflected from an entire hemisphere, and it must be analyzed in complicated ways before it yields information about details on the hidden surface of the planet.

The first step in this involved series of deductions requires the location of the general areas reflecting parts of the beam—a seemingly impossible task that is accomplished by extremely delicate clocking of the echoes. The waves reflected by the nearest part of Venus, the center of the hemisphere facing earth, will get back to the earth first, followed by waves from more distant parts. The edges of the disk, which are about 4,000 miles farther from the earth than the center is, will be heard from last. These time delays can be measured very accurately to identify the area that is being heard from. In this way the echoes are traced to successively larger and more distant ring-shaped zones on the planet.

Such rough locations of the sources of the echoes can then be com-

bined with measurements of the intensities of the echoes to reveal surface prominences. If Venus were perfectly uniform all over its surface, the amounts of energy reflected by each of the concentric zones would follow a pattern predicted by theory. This is not what happens. Some of the zones return more energy than they theoretically should, indicating that they contain one or more highly reflective regions. By analyzing the time delay in the radar signal, scientists can place these highly reflective regions within particular zones. The true position within each zone can then be estimated because the reflecting area moves as the planet rotates, and the reflected waves therefore exhibit a Doppler shift, which can be measured. This complex technique permits a crude map of Venus to be drawn. Radar astronomers have become so clever at this sort of thing that they can watch certain reflective objects appearing at one edge of the cloud-covered planet, moving slowly toward the center and disappearing over the opposite edge.

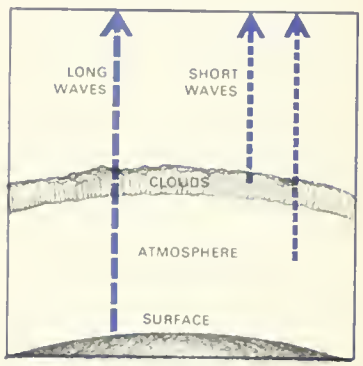
It is these reflective objects that some observers have identified as mountain ranges resembling those on the earth. One range, called the Alpha mountains, is perhaps 2,400 miles long and runs roughly north and south, while the Beta mountains run east-to-west and may be even longer. Both Alpha and Beta seem to be several hundred miles across and show hints of a complex structure. They may be made of multiple ridges, as the earth's mountains often are. Or they may have a kind of topography unknown to the earth and not yet identified elsewhere in the solar system.

Ice crystals above a red-hot surface

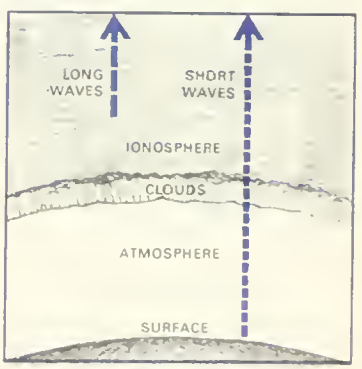
The Venus detectives have now collected enough information about the planet to give some idea of its climate and scenery. The atmosphere is heavy, 30 or so times as dense as the earth's, so even gentle winds will raise dust storms. Roughly 40 miles above the surface hang the eternal clouds made of ice crystals on their tops and water droplets lower down. If there are breaks in the clouds, the clear sky that shows through has a yellowish-green tinge. The sun, in its rare "appearances," is deep brick red. Violent storms may toss the clouds into towering billows, but any rain that falls from them evaporates in the hot, dry atmosphere before it comes near the ground.

Most of the planet's surface is rather smooth, probably made of loose dust glowing dull red in shadows and hot enough to char any organic matter. Exposed rocky surfaces may be wind-eroded, showing curved and hollowed shapes like rocks exposed to sand-laden winds on the earth's waterless deserts, but this is by no means certain.

Besides its atmosphere and surface, so different from the earth's, Venus seems to have a different interior. Instruments carried by Mariner II showed that its magnetic field is weak or nonexistent, and this is fairly good evidence that it does not have a core of liquid iron like the earth's. It is likely that iron was plentiful in the original material of which the planet was formed; if the iron did not migrate toward the center, as most



TWO MODELS OF VENUS have been postulated to explain the fact that the planet emits both long and short radio waves. Some observers once favored an "ionospheric model" *(below)*, showing a relatively cool (200° F.) surface which radiates short waves, and a thick ionosphere which radiates long waves. But data transmitted by the U.S. spacecraft Mariner II during its 1962 flight past Venus have convinced astronomers that the ionosphere is not dense enough to produce long waves. They now favor a "greenhouse model" *(top)*, where the planet's surface, heated to 800° F. by the greenhouse effect *(opposite)*, radiates the long waves, while the short waves come from the atmosphere and clouds.



of the earth's iron did, it may have stayed close enough to the surface to combine with oxygen, thus accounting for the absence of oxygen in the atmosphere.

Venus is now known to be so hot and dry that there is little hope of finding life on its surface. Even if a little liquid water exists near the poles, it will be hot enough to destroy the complex organic compounds, such as proteins and nucleic acids, that are the chemical basis of the earth's life. There may be different kinds of life elsewhere in the universe, but the heat of Venus would probably be fatal to them too.

There is a small possibility, of course, that Venus was cooler in the remote past and had liquid water in which life developed. If living organisms did appear, they might have evolved fast enough to adapt themselves to the increasingly hostile climate, perhaps by taking refuge in the clouds, and thus to stay alive.

But such possibilities seem unlikely. When a heat-proofed space probe is sent from the earth to the searing surface of Venus, it will probably find no life and no sign that life ever existed there. Organic molecules from the early history of the solar system will be absent also. The heat of Venus will not preserve them as the deep freeze of the moon would.

Colonizing Venus

And yet, dead as it seems today, Venus need not be written off forever as an abode for life. It is potentially fertile. It has water, carbon dioxide and light, the essential requirements for photosynthesis. Nitrogen, essential to earthly life, probably forms the bulk of its atmosphere. All the minor elements needed by life, such as phosphorus, magnesium, etc., are believed to exist in its dusty surface. So although Venus may be unable to develop life of its own, it offers a possible field for colonization from the earth. This might be attempted after an intermediate period of what can be called "microbiological planetary engineering."

No one who has studied the swarming, varied life of the earth fails to be impressed with its amazing ability to adapt itself to a wide range of environments. Microorganisms thrive in hot springs, on snowfields, in saturated brines, in the pressure, dark and cold of ocean bottoms. It is not inconceivable that an organism can be found or developed that will live and thrive somewhere on Venus and, in time, make it inhabitable for higher forms of life.

The one place in Venus where colonies of living things might be planted is in the clouds. Their bottom levels probably contain water droplets at a temperature of about 15° F., providing conditions which, laboratory experiments indicate, may support life. To be suited to life in the clouds of Venus, the microcolonists must be able to extract water from the clouds or the atmosphere and turn gaseous nitrogen into nitrogen compounds for use in their body chemistry. They must live a wholly aerial life, suspended by the turbulence that stirs the clouds. They must resist ultraviolet light and reproduce rapidly whenever carried to places where conditions are favorable.

These seem tough requirements, but the earth's microorganisms have recently shown what they can do by adapting themselves in a few years to remarkably hostile new conditions. Some of them have set up housekeeping in the fuel tanks of jet planes, where they live on kerosene and do not seem to be bothered by violent changes of pressure and temperature. Another group has learned to live in the cooling water that circulates through the cores of nuclear reactors, where the radiation would kill a human being quickly.

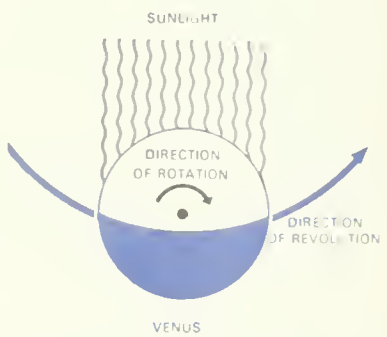
Such achievements by the earth's humblest inhabitants are encouraging to the microbiological planetary engineers, who hope that scientifically selected organisms will do even better. The most promising species to start with are blue-green algae, which already have many of the needed abilities. If they are subjected in the laboratory to increasingly rigorous conditions for years or decades, strains may emerge that can thrive in the clouds of Venus. Transporting them to their new home will not be difficult, even with existing space vehicles.

According to one speculation, the arrival of micro-Pilgrims in their space-borne *Mayflower* may have a dramatic effect on Venus. Once they are established and begin to multiply rapidly, they will abstract large quantities of water and carbon dioxide from their cloud homes and they will break down these substances by photosynthesis, manufacturing food and discharging oxygen into the atmosphere. The bulk of the organic matter that they make in this way will be carbohydrates, which can be considered as combinations of carbon and water. When any of the microorganisms fall into the hot lower atmosphere or are carried there by down-currents, they will be charred to black carbon by the heat. The water in them will be released to return to the atmosphere while the carbon will be deposited on the surface far below.

Making Venus habitable

If these reactions continue long enough—and this need not be very long—they will take much of the carbon dioxide out of the atmosphere, replacing it with oxygen. Since the high temperature of the surface depends in part on the greenhouse effect of carbon dioxide, the surface will then cool down. If it gets cool enough for rain to collect at the poles as liquid water, the greenhouse effect of water vapor in the atmosphere will be reduced also, causing additional cooling. When more rain falls, the heat-retaining clouds will partially clear away, leaving a planet with an oxygen-rich atmosphere and a temperature cool enough to sustain hardy plants and animals from the earth. It may even be suitable for human colonization.

Human colonies for an ice-clouded, red-hot planet may seem fantastic. But the fact that such a prospect can now be entertained is a tribute to the power of the astronomer's techniques, which have revealed the topography, climate and atmosphere of a planet whose surface no man has seen. From 36 million miles away, ingenious instruments and sophisticated deduction are solving the mystery of the veiled planet.



THE ROTATION OF VENUS around its axis presents astronomers with a mystery they cannot yet explain. When viewed from above their north poles, most planets (e.g., earth) rotate counterclockwise, or directly *(below)* —the same way that they revolve around the sun. But Venus' rotation *(above)* is clockwise, or retrograde, and opposite to the way it revolves around the sun.

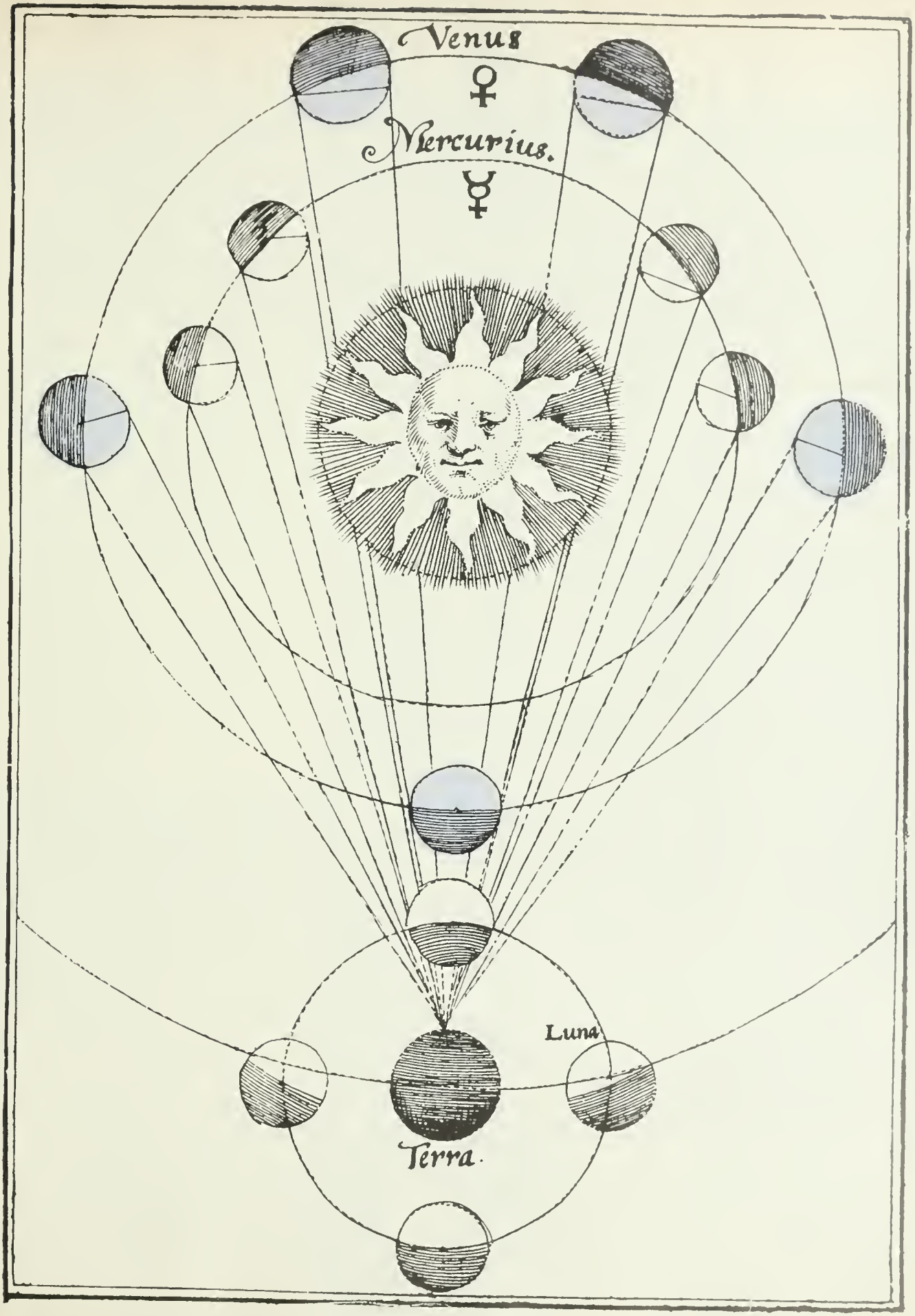
Venus: Roasting under Ice

An old fable tells of a blind man who felt an elephant's tail and concluded the animal was made of rope, while another grabbed its trunk and described it as a snake and another felt a leg and decided it was like a tree. Astronomers have had the same trouble with Venus. No one has ever seen its cloud-shrouded surface, and for centuries there were not enough facts to draw a picture from. Galileo discovered the planet's phases *(right)* in 1610, but that gave no hint about its physical appearance. The presence of an atmosphere was deduced in 1761. Until recently, little else was known.

Speculation based on such scanty information produced an intriguing variety of concepts. One writer thought Venus was populated by reptiles. Others saw it as a steamy swamp, as a place enveloped by dust clouds, as a sea of carbonated water, or as an ocean of oil. Only by arming themselves with instruments that can "see" through the clouds have astronomers finally been able to start solving the puzzle of Venus. With data from radar, radio telescopes, infrared detectors and space vehicles they are now able to draw with some confidence a picture of the earth's mysterious neighbor.

EXPLAINING THE PHASES

An explanation of the phases of Venus and Mercury was drawn in 1643 by the Swiss mathematician Matthias Hirzgarter. As the planets travel around the sun, half the surface of each is always illuminated; but since their orbits are inside the earth's, the visible portion of their lighted surfaces, as seen by an observer on the earth, gradually decreases as they approach the earth


Venus
♀
Mercurius.
☿
Luna
Terra.

PHASES FROM FULL TO CRESCENT
Venus, seen through a telescope, appears full when it is on the far side of the sun. As it nears earth it becomes a thin crescent. Then, almost between the earth and the sun *(bottom)*, Venus is distinguished by a fuzzy partial halo created as sunlight is scattered by its atmosphere.

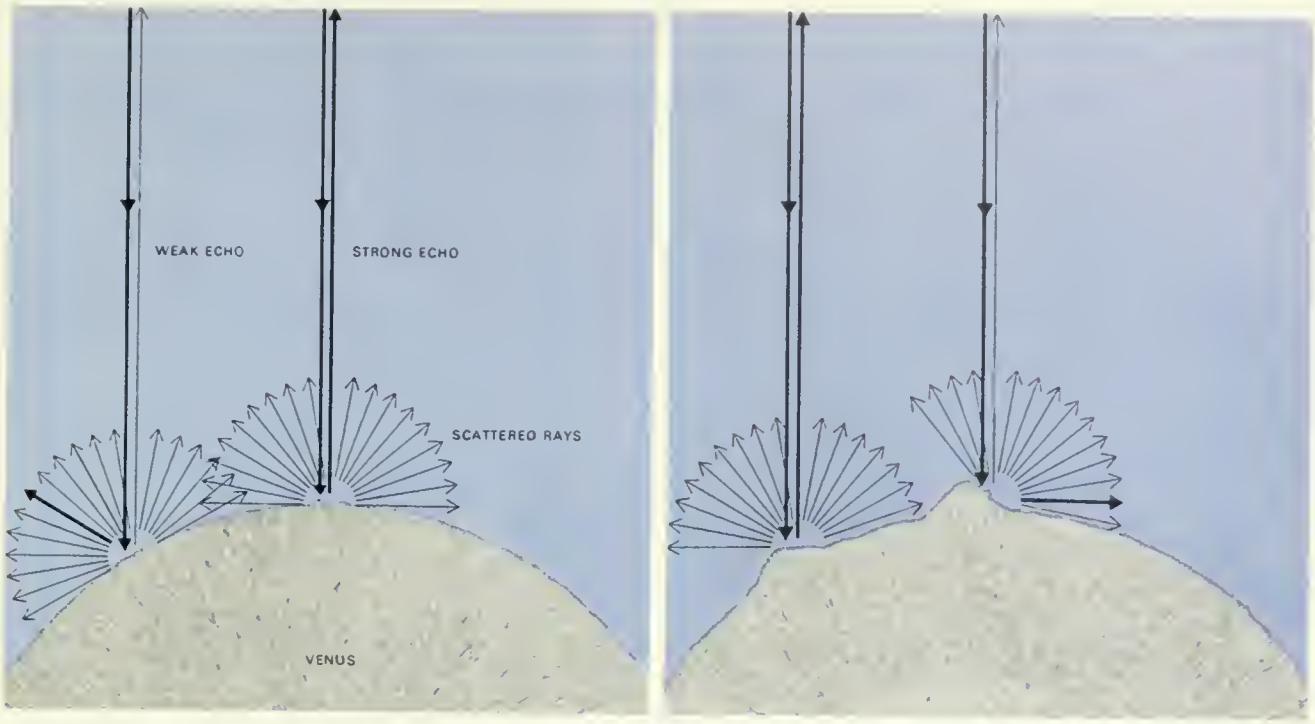
Charting the Unknown

The optical telescopes which have revealed so many secrets in the skies are very little help in solving the puzzle of Venus. They revealed its dense atmosphere and helped plot the planet's phases as it swings between the earth and the sun every 584 days; and some astronomers have thought they have seen through a telescope shadowy markings on the planet's cloud layer. But observers seldom agree on what they have seen, and no visible-light photographs have ever confirmed their findings.

But that there are shadings of some sort within the cloud layer has been proved by ultraviolet photographs, pictures taken on film sensitive to radiations whose wavelength is just a little shorter than visible light. These markings are now taken to indicate billows and shifting winds on the planet's cloud face.

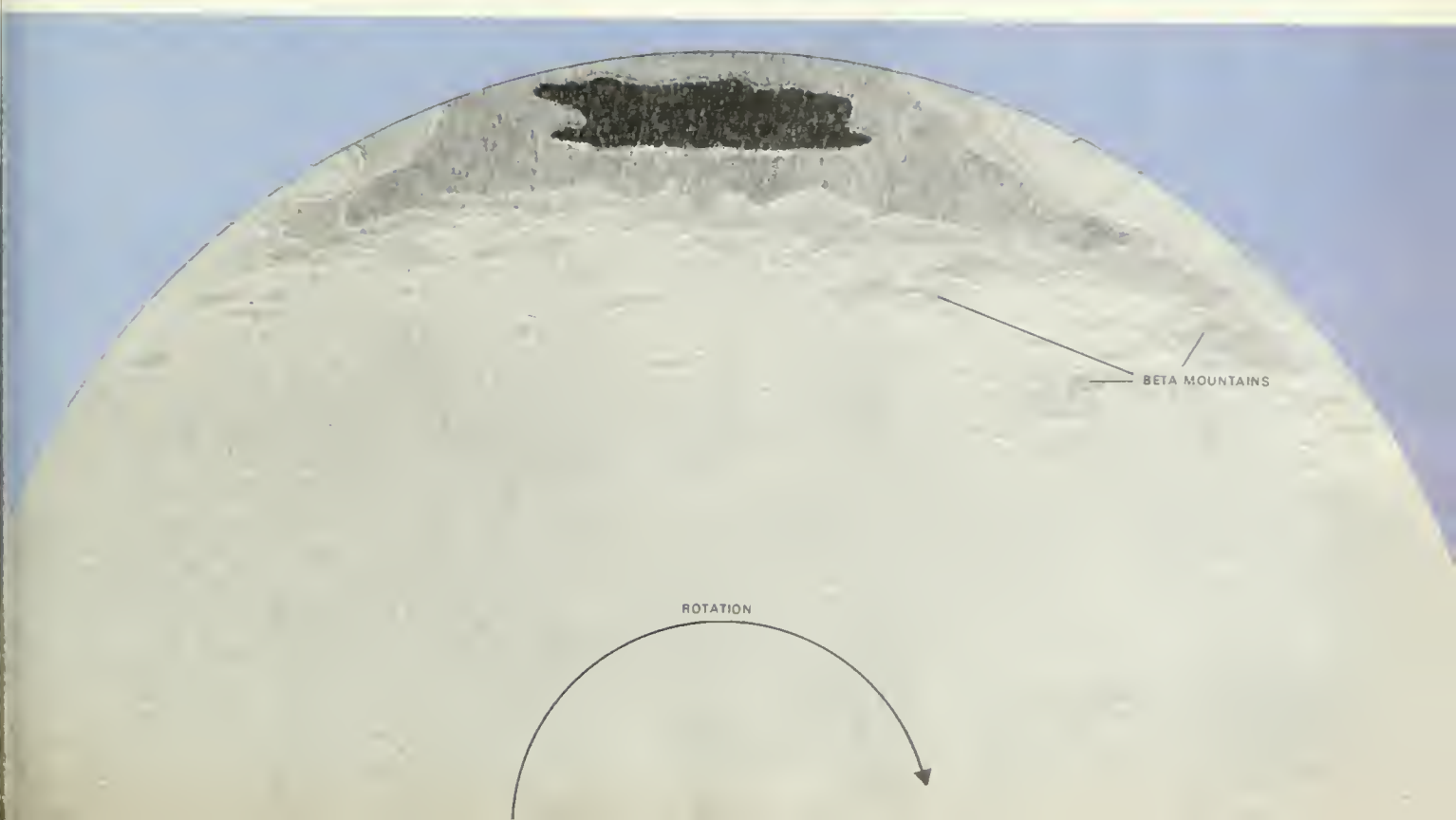
A start has also been made in the much more difficult job of charting the planet's surface. The key tool is radar, which bounces signals off Venus and analyzes the faint echoes. Radar not only has enabled astronomers to probe the planet's hidden topography but has told them that Venus rotates the "wrong" way, that its day is about 250 earth days long and it has, in effect, only one season.

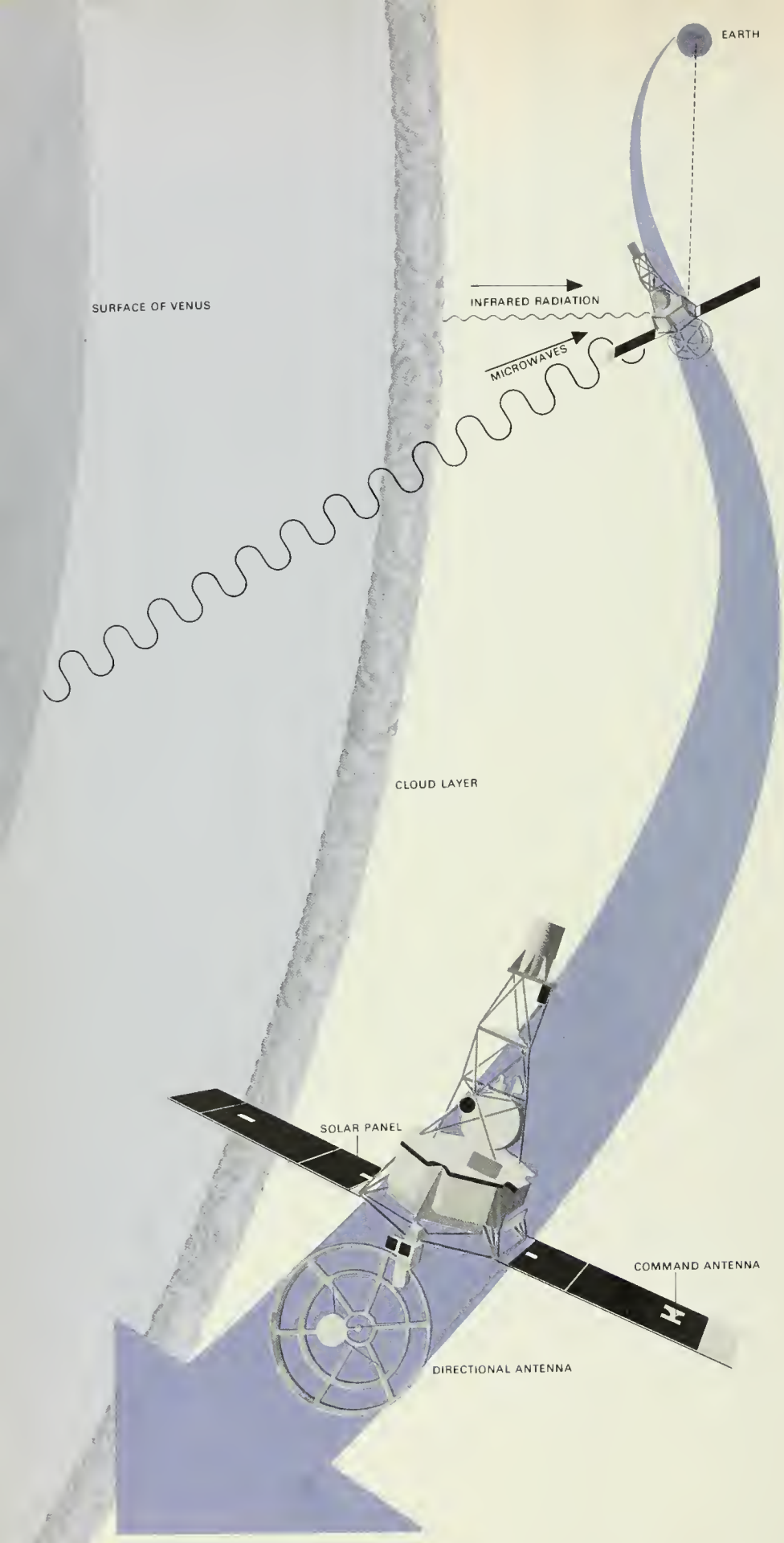
VENUS BY ULTRAVIOLET
Ultraviolet photographs, taken at Lowell Observatory in Arizona reveal dark patches in the clouds of Venus. The patches change in appearance and location from day to day, suggesting that they may be caused by billowings in the planet's cloud layer, produced by strong winds.



MAPPING BY RADAR

The tentative map of Venus below is based on interpretations of radar signals as illustrated above. At left above, the signals are shown bouncing off a smooth surface. Only the center of the curved surface reflects a strong echo *(thick arrow)* back to earth. Where the surface curves away the rays bounce off at an angle, so that the planet's edges return only weak signals to earth. If, however, the radar rays bounce off irregularities such as mountains, the patterns are changed *(right, above)*. In what is otherwise an area of weak echoes, strong ones come bouncing back from the oblique surface; radar rays striking at a different angle bounce their strongest signals off to one side, and only weak scattered signals return to earth. In the map below, the dark area indicates the range of normal strong echoes, gradually weakening away from the central area. To the west *(right)* something has sent back stronger echoes than anticipated. This area is called the Beta mountains. Whether it actually is a mountain range may be learned from the data obtained from the Russian and American Venus probes of 1967.





First Report from Out There

In December of 1962 the unmanned spacecraft Mariner II performed what was at the time man's most impressive space feat: the first closeup look at another planet. From 21,600 miles away, Mariner radioed back a report on Venus that, while far from comprehensive, carried information that no earth-mounted telescope, radar or camera had provided.

Two important parts of Mariner's report came from compact detectors designed to pick up certain microwaves, which gave information about surface temperatures, and infrared radiation, which provided data on the temperature of the cloud cover. Astronomers hoped that Mariner II could detect variations in intensity of the radiation that would determine whether Venus' high temperature readings came from its atmosphere or its surface. They were not disappointed. Mariner, operating on command, obediently took its readings from several different angles and settled a long-standing argument: Venus' surface is extremely hot (averaging about 800° F.), but its cloud layer is very cold (averaging −40° F.).

A FAST FLYBY
After a 109-day trip covering 180 million miles, Mariner II spent 35 minutes "listening in" on Venus before continuing in its long orbit around the sun. Its detectors monitored radiation which confirmed the planet's surface and cloud-layer temperatures. Mariner II also discovered that Venus has no apparent magnetic field, and that, unlike earth, it has no enveloping belt of charged particles. These findings were beamed to earth by Mariner II's directional antenna (shown reversed for this illustration), orders from the earth were received by the command antenna.

A DUSTLESS CHECKUP
Surgically garbed technicians in a dust-free chamber prepare Mariner II for its trip to Venus. The 447-pound craft, partially coated with gold and aluminum as protection against the sun's heat, has 10,700 solar cells which convert sunlight into electrical power for the equipment.

Two Versions of Venus

Before modern astronomical instruments began to unlock Venus' secrets, scientists relied mostly on educated guesswork to concoct descriptions of the planet's surface.

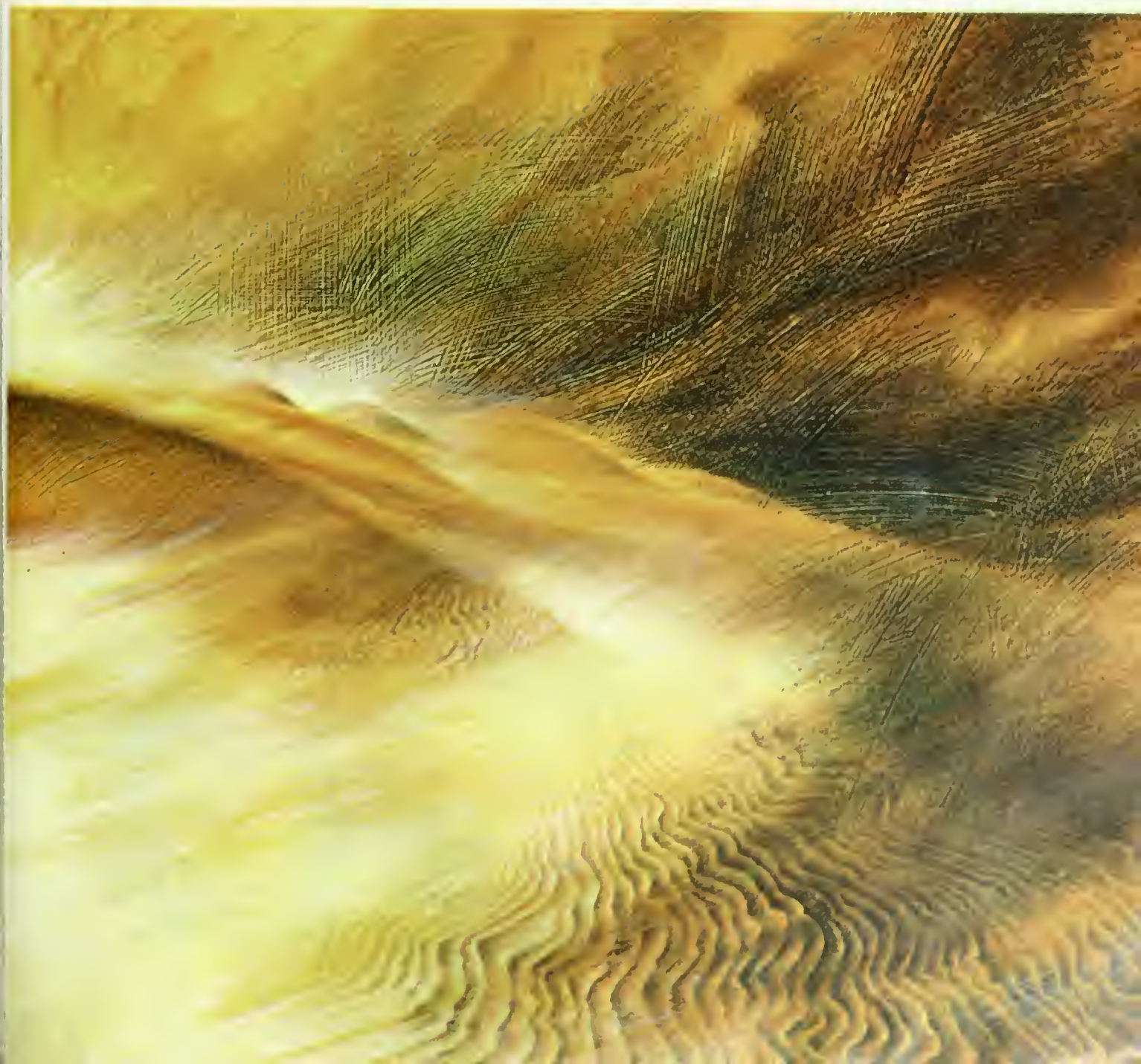
In 1918, a Swedish chemist named Svante August Arrhenius suggested that the clouds veiling the planet must be composed of water, as are earth's clouds, and that the planet must be a vast swamp *(below, left)*, resembling the swamps of the earth's Carboniferous era some 280 million years ago. Arrhenius concluded that temperatures, averaging about 120° F., caused vegetation to grow at such a furious rate that plants died rapidly and their decaying bodies filled the air with stifling gases. Beneath the swamps he envisioned great beds of coal. Arrhenius was vague about the possibilities of animal life. He did say, however, that "progress and culture" were more likely at the poles than at the hotter equator.

In 1922 the American astronomers

A STEAMY SWAMP

Charles St. John and Seth B. Nicholson revolted against the "wet Venus" theory, and formulated a hypothesis that stands up better today than even some more recent ones. After painstaking spectroscopic study of light absorption by molecules in the planet's atmosphere, they concluded there was "no appreciable amount" of water vapor or oxygen on Venus (recent studies have revealed that traces of water vapor exist above the clouds, but no oxygen). They suggested that the surface of Venus was a windswept desert *(below, right)*, and the clouds were great billows of dust swept up by furious winds circling the planet. Their concept was quite different from Arrhenius', because they had one more piece of data to work with. And their final speculation—that the atmosphere of Venus may contain considerable carbon dioxide—was proved correct a decade later when large amounts of carbon dioxide were indeed discovered.

A DUSTY DESERT



A Seltzer Sea, an Oily Ocean

When a spectroscopic study in 1932 detected abundant carbon dioxide in the atmosphere of Venus, astronomers acquired a key fact on which to base their speculations about the planet. By 1955, two new models of Venus had been devised to take into account the discovery.

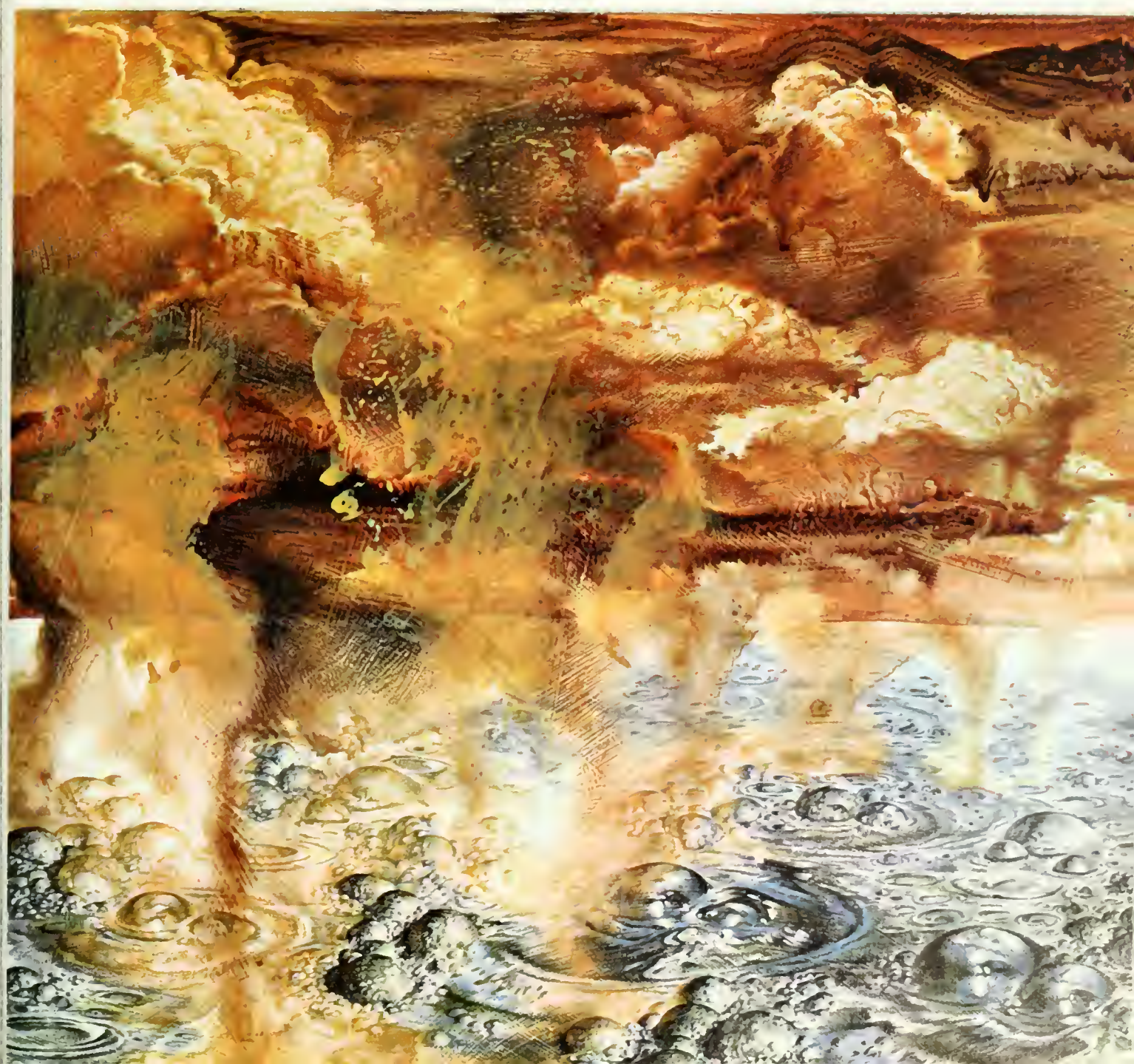
The first tried to explain the carbon dioxide in terms of one theory about the earth's atmosphere. On earth great quantities of carbon dioxide have been released from the interior, but most of the gas has combined with silicate materials to form carbonates like limestone or chalk. Why hadn't this happened on Venus? Some astronomers hypothesized that the surface of Venus might be almost entirely covered with water *(below, left)*, leaving nothing to use up the carbon dioxide. The water would be charged with carbon dioxide, forming a seltzer-water sea. Islands thrusting above the surface would have limestone crusts, and erosion would grad-

A CARBONATED SEA

ually wear them down to the surface.

The other hypothesis offered a different explanation of how the carbon dioxide got into Venus' atmosphere. It argued that Venus at one time had some water and vast amounts of oily hydrocarbons, perhaps like petroleum. Ultraviolet rays from the sun split the water molecules into hydrogen and oxygen, and then the oily hydrocarbons combined with the oxygen to form carbon dioxide. Eventually, all the water was used up, and nothing was left but carbon dioxide and huge quantities of hydrocarbons forming a vast ocean of oil, possibly bubbling with natural gas. "Venus is probably endowed beyond the dreams of the richest Texas oil-king," said one proponent of the concept. In this model of Venus the clouds consist of a heavy smog of oily droplets, instead of water droplets. Since practically nothing was known about the makeup of Venus' clouds at the time, the hypothesis was not unreasonable.

A PETROLEUM PLANET



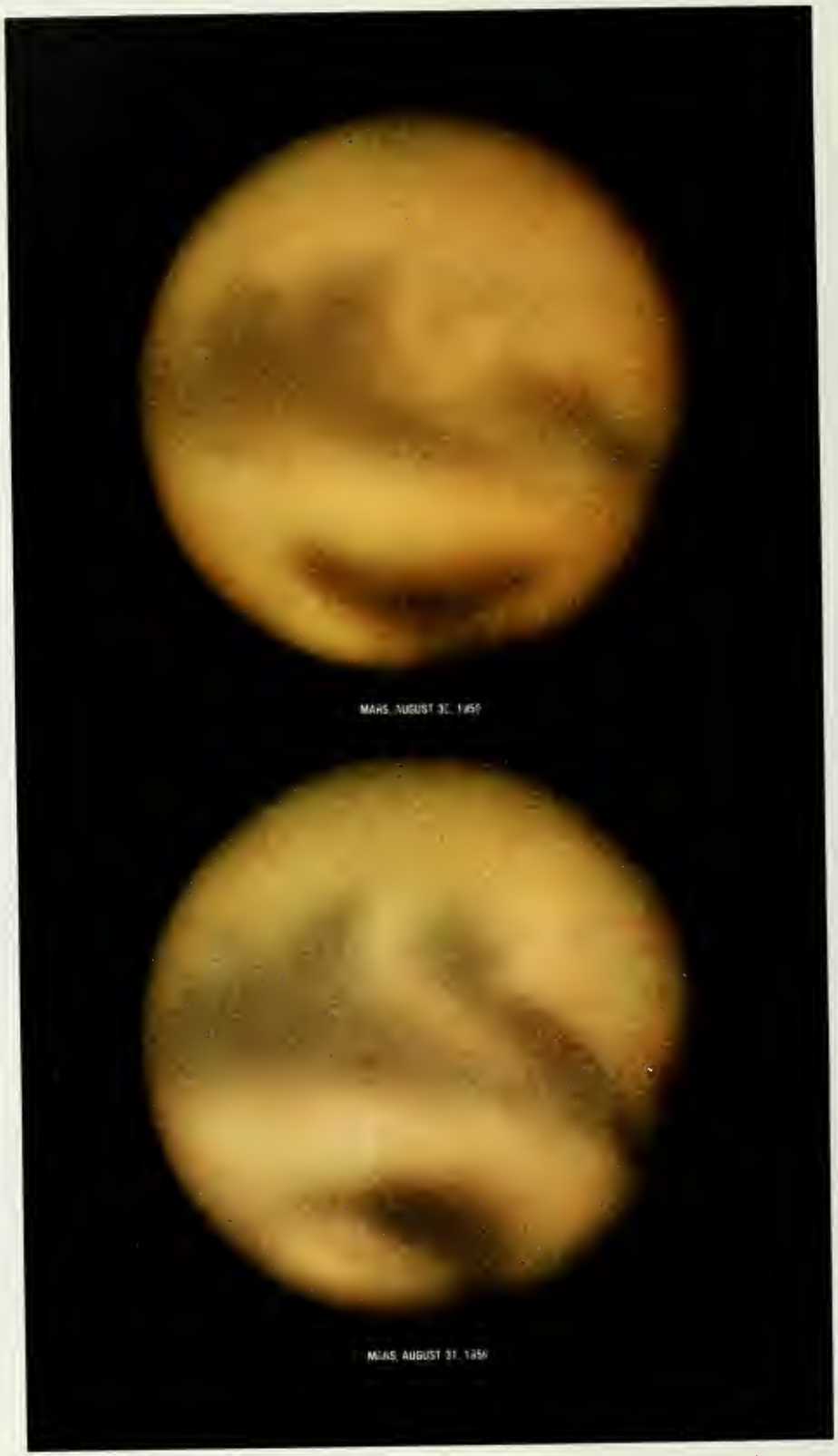
A Forbidding Picture

After 1956 a reliable picture of Venus began to emerge at last—a surprising picture of a searingly hot, bone-dry planet surrounded by clouds of ice. Radio telescopes reported conditions so extreme as to rule out completely a surface of either water or oil: temperatures measured from the sunlit side averaged 800° F. and went as high as 1,300° F.

The heavy layer of carbon dioxide, water vapor and ice crystals in Venus' atmosphere acts as an enormously effective blanket, holding in the heat of the sun. The atmospheric pressure under this cloak would be some 30 times greater than that on earth—the equivalent of the pressure exerted on a submarine 980 feet down. No erosive water can exist, but billions of years of wind-borne sand erosion have probably sculpted any existing rocks into eerie shapes resembling the strange formations called yardangs that are found in some deserts of Central Asia.

The sky must be overcast most of the time, but midday sunlight filters through. In the shadowed areas the surface must glow a dull red. So it seems, after all, that Venus is a very forbidding place. Except at the bottom of the clouds, where water droplets may exist, no place on Venus appears suitable for any forms of life.

6
The Red Planet



A huge dust storm *(top)* obscures Mars's normal face *(bottom)* in pictures taken a day apart.

From the point of view of the earth's inquisitive inhabitants, the most interesting planet in many ways is Mars. Its atmosphere is thick enough to give it a climate and weather of a sort, but its clouds do not hide the surface the way the clouds of Venus do. Like the earth, it has white polar caps, and its surface changes shade with the advance of the seasons.

These earthlike properties have suggested strongly to some that Mars is inhabited by a kind of life not very different from the earth's. Indeed the planet has appeared, superficially, to be so hospitable that many writers, not all of them consciously writers of fiction, have peopled it with intelligent beings at least as advanced as man. While such an extreme view is not now favored by the great majority of astronomers, many of them believe that Mars could maintain life. Direct observation has lent credence to such a theory, and this is true of no other planet—a fact that puts Mars in a special class of its own.

The likelihood that life might exist on Mars does not depend on the planet's similarity to the earth. In major physical respects, Mars is less like the earth than Venus is. Its diameter (4,220 miles) is a little more than half of the earth's, and its mass is about one tenth. It follows an orbit considerably more elliptical than the earth's, with a mean distance from the sun of about 140 million miles, more than 50 per cent greater than the earth's. Sunlight on Mars is, on the average, less than half as strong as on the earth, and this makes the planet much colder.

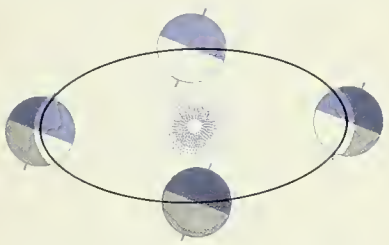
The features that suggest life on Mars are hard to see. In spite of its generally clear atmosphere, the planet is an exasperating target. Even through a large telescope it looks like a small, reddish-orange ball, fuzzy at the edges and usually shimmering slightly because of turbulence in the earth's atmosphere. The untrained eye sees little except the white polar caps, at least one of which is usually on view, and a few dark mottlings. But if the observer persists and is favored by nights of good seeing, the fuzzy ball develops a personality. The dark blotches become familiar. They acquire sharper outlines, and smaller markings appear between them. At last comes a rare instant when the air overhead stands still. The fuzzy ball snaps into sharp focus, revealing hundreds of small and varied details, far too many to be remembered. Then everything abruptly disappears, leaving the observer with the feeling of having just missed a glorious revelation. Frantically he sketches a few details, then eagerly looks forward to the next rare instant of perfect seeing.

Even the best photography does not catch these elusive glimpses because there is no way to anticipate the brief intervals of perfect seeing and take a picture at the right time. So until 1965, when the U.S. spacecraft Mariner IV took its spectacular closeup pictures of Mars, the best detailed knowledge of the Martian surface was the product of years of patient work at the telescope by many highly skilled visual observers. Though their sketches were much more detailed than existing photographs, they were not always accurate or in agreement.

Out of this disagreement grew the great canal controversy, perhaps

the gaudiest episode in the history of modern astronomy. In 1877 the Italian astronomer Giovanni Schiaparelli announced he had observed on Mars a network of thin straight lines. He called them *canali*, which means "channels" in Italian. He did not claim they were artificial, and he may have been startled when the American astronomer Percival Lowell declared them to be "canals." They were, said Lowell firmly, irrigation canals dug by highly civilized Martians to transport water from the melting polar ice caps. The Martians, he explained in a series of articles, books and lectures, were in a difficult position. Their planet was drying up, and they had to make the best use of the remaining water.

The more Lowell studied Mars the more canals he saw; his later maps of the planet were cobwebbed with them. They were more than canals, he said. Actual watercourses were too narrow to be seen, but on both sides were cultivated fields where the Martians grew their irrigated crops. In certain places where the strips crossed were broad oases, presumably the major centers of Martian civilization.



THE CHANGE OF SEASONS on a planet is due to the tilt of its axis of rotation. If the axis were perpendicular to the plane of its orbit, there would be no seasons. But when the axis is tilted, alternate hemispheres receive more than their share of solar radiation at different times of the year. For half a year, the north pole leans toward the sun, causing the sun's rays to strike the northern hemisphere *(blue area)* more directly. Then, for the rest of the year, the south pole leans toward the sun, and the southern hemisphere receives stronger sunlight.

The "cities" of Mars

This beguiling concept won passionate adherents who equipped Mars with everything that a civilized planet should have: ships on the canals, gorgeous cities in the oases and enormous engineering works to make the water flow. Lowell also had opponents who looked at Mars and saw nothing but vague light and dark patches uncrossed by any kind of line, straight or otherwise. Some of the most experienced visual observers took a middle position. Under superb seeing conditions they occasionally saw great numbers of mottled details on Mars but did not know what to make of them. They suspected that Lowell and his followers were glimpsing the same details at the far limit of vision and permitting their eyes or imaginations to string them together into straight "canals."

The canal enthusiasm died down when better instruments and subtler means of interpretation showed that conditions on Mars are far from compatible with a high civilization of earthly type. But the pictures transmitted to earth by Mariner IV showed that Mars is richer in detail than even Percival Lowell claimed it to be.

Just what is there on Mars? Even the crude view of Mars available from the earth shows diverse and changing conditions. Mars has several kinds of clouds in its atmosphere; it undergoes an annual march of the seasons, which seems to change the properties of large areas, and its topography may be as varied as the earth's.

As seen from the earth, the planet has three general types of surface. Most conspicuous are the dazzling white polar caps. The southern cap disappears entirely during the southern summer, but the northern cap always leaves a small patch when it, in turn, recedes.

Next in prominence are irregular areas of orange ocher that cover perhaps two thirds of the planet. They are usually called deserts, though early observers often gave them idyllic names such as Elysium and Eden. Among them are darker patches that bear the names of bodies of water,

like the moon's maria. They have sometimes been described as green, but astronomers who have compared views at the telescope with painters' color charts see the dark patches as various shades of gray or gray-brown. These are the parts of Mars that show the most interesting seasonal changes and have received the most rapt attention.

Because the Martian axis is tipped at about the same angle as the earth's, Mars's polar regions are exposed to sunlight in alternation, just as the earth's are, giving each hemisphere summer and winter. But Mars takes 687 days to orbit the sun, which means that its year is a little less than two years long, and its seasons are double the length of the earth's.

Spring in reverse

The seasons bring remarkable surface changes on Mars, changes that are suggestive of those on earth. When spring comes to the earth's Northern Hemisphere, the snow cover in North America and northern Europe and Asia gradually shrinks, retreating toward the Pole, and a little later the land changes color from south to north as grasses grow and deciduous trees put out new leaves. On Mars a rather similar change occurs, but the direction is reversed. When one of its polar caps shrinks, a "wave of darkening" moves away from its retreating edge and advances toward the Martian equator at about 20 miles per day. This wave affects chiefly areas that were already rather dark, while the lighter deserts remain almost unchanged. It is tempting to conclude that water released by the shrinking cap has stimulated Martian vegetation into vigorous springtime growth. An observer with an active imagination can almost hear the Martian birds sing.

Formidable attacks have been made on this attractive idea of burgeoning vegetation. Water is very scarce on Mars. The polar caps are generally believed to be made of some form of frozen water which, like the frost on windowpanes on cold winter nights, is deposited directly from water vapor. The Martian frost does not melt to form liquid water; the pressure of the atmosphere is so low that ice turns directly to water vapor without passing through the liquid stage, just as dry ice turns directly into carbon dioxide gas on earth. The springtime growth of Martian vegetation, if it takes place, must depend on the seasonal arrival of water vapor, not on anything like rain or freshets of liquid water.

The atmosphere has other properties that are not favorable to familiar kinds of life. It has long been known to be thin, but Mariner IV proved it to be even thinner than had been supposed. As the spacecraft began to pass behind Mars, its radio signal to earth briefly traversed deeper and deeper layers of the Martian atmosphere. Fading of the radio waves enabled scientists to determine that Mars's atmospheric pressure at the surface is about 1 per cent of the earth's, or as thin as the earth's atmosphere 20 miles up.

For the earth's higher organisms, so thin an atmosphere would be immediately fatal, even if it were made of pure oxygen. Actually, no oxygen has been detected in it, and there can be no more than a trace. The

A ROCKLIKE MARS is shown in this 17th Century engraving by Matthias Hirzgarter. Hirzgarter, a Swiss mathematician, used data obtained from the Italian astronomer Francesco Fontana to postulate that the planet was a huge, triangular-shaped rock. Because of a faulty telescope, Fontana had mistaken certain dark markings on Mars—the Syrtis Major region—for the planet itself. The traditional symbol for Mars appears on the rock

Martian atmosphere is apparently composed of carbon dioxide and a lesser fraction of nitrogen. It contains a small amount of water vapor that is believed to vary in concentration from place to place, but is never as abundant as over the earth's driest deserts.

Though the Martian atmosphere supports clouds, some of ice crystals, others of yellowish dust, it does not contain enough heat-trapping gases to hold much of the sun's heat. It is not nearly so effective a "greenhouse" as the earth's atmosphere is. This, plus the dryness of the surface, enables the scanty heat that reaches Mars from the sun to escape easily. The temperatures of the different zones can be measured separately by infrared light, and nowhere is the climate tolerable by human standards. Near the equator at noon the surface temperature may rise to 70° or 80° F., but during the night it plunges to −120° F. The poles in winter are even colder. Radio astronomy tells a similar story, indicating that about one foot below the surface the average temperature is an almost steady −80° F. The fact that the surface warmth does not penetrate more than a few inches suggests that Mars has a layer of insulating dust like the moon's.

Seasonal winds of change

All these hostile conditions—cold, extreme dryness, low pressure and lack of oxygen—have led astronomers to search for some nonliving substitute for the dark stuff that seems to grow in some areas during the Martian spring. One of these hypotheses proposes that the dark areas may be highlands that are normally covered with a mixture of dust of varying fineness. Since fine dust generally appears brighter than coarser grains of the same material, the wind that blows the smallest particles away will make the highlands look darker. Perhaps such winds do blow in the Martian spring, while winds that blow at other periods of the year have the reverse effect. They may lift light-colored dust from the deserts and sift it thinly over the highlands, returning them to the lighter shade that they show in winter.

This view gains support from studies of sunlight reflected from the dark areas. Changes in the light during reflection indicate the size of particles on the surface. Apparently the dark areas are indeed covered with larger particles than the light-colored deserts. Surveying the surface with radar offers additional evidence in support of the dust theory by indicating that the dark areas are higher than the deserts. If they were lower, dust blown from the deserts would have covered or filled them long ago, and the surface change would no longer take place.

The closest view of the Martian surface, obtained by Mariner IV, renewed the controversy over life on Mars. When the spacecraft passed within 6,200 miles of Mars, it made pictures showing circular shapes which are undoubtedly meteorite impact craters like the moon's.

The craters are of all sizes, from three miles in diameter to 75 miles, and apparently they are of different ages. The largest has only half its rim; the rest has been obliterated, though not by later impacts. Many of

the craters are shallow, round depressions without visible raised rims and are apparently filled almost to the level of the ground around them. The filled-in appearance is most prominent in the light-colored deserts, and this is what would be expected if the deserts are lowlands exposed to drifting dust. But craters on the uplands are partially filled and have a worn look, probably caused by erosion.

Some astronomers had predicted meteorite craters on Mars, but the pictures were generally a surprise. The 70 craters were clearly pictured on about 1 per cent of the Martian surface, and astronomers estimated that the entire planet must have something like 10,000 craters within the same size range and must look much like the moon. The surface of the airless, waterless moon is known to be extremely ancient, perhaps two to 4.5 billion years old. It is as well preserved as it is because it has escaped wind and water erosion for all that time. If the Martian surface is similar, according to one line of reasoning, it must be just as ancient. If it also shows no sign of water erosion, Mars can never have had much atmosphere or liquid water. Without them the planet is unlikely to have supported life at any time in its history.

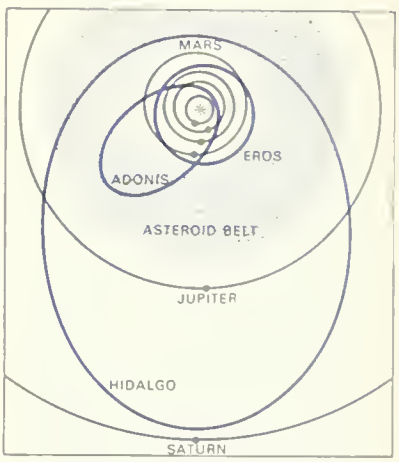
A bad neighborhood for a planet

This pessimistic conclusion was quickly challenged. Mars lives in a bad neighborhood of the solar system, where flying rocks are a frequent hazard. Between the planet's orbit and that of Jupiter lies the asteroid zone, where thousands of objects, presumably debris from small broken planets, revolve around the sun. There are probably 50,000 asteroids big enough to be seen with large telescopes. Most of them stay in their proper zone, but a considerable number wander eccentrically.

Along with the visible asteroids move uncounted millions of meteorites too small to be seen but large enough to blast conspicuous craters in any planet they hit. The earth and moon have suffered many of these impacts, and Mars, being closer to the asteroid belt, must have had many more. It has been estimated that during any selected period Mars must have been hit by about 25 times as many meteorites as hit the moon. If the planet's surface were really ancient and free of significant erosion, it should be much more pitted than the moon's. Since it is not, erosion must be very effective on Mars and its surface must be younger than the moon's. Astronomers have calculated that none of the features that we see can be older than 800 million years, a small fraction of the age of the planet itself, nearly five billion years.

Something must have eroded the ancient craters of Mars's youth, and the most likely agents are water or wind. Though the planet has no oceans now and lacks a substantial atmosphere, it may have had both in the past. If it had, it may have been much more favorable for the development of life than it is now.

Not much is definitely known about the early history of Mars, so conjectures are necessarily vague. The present thinness of its atmosphere is especially hard to account for. Soon after its formation, Mars was pre-



THE ASTEROID BELT, extending between Mars and Jupiter, was once thought to be composed of orbiting fragments of an exploded planet. Many astronomers now believe that the asteroids, sometimes called minor planets, are masses of rock and metal that might have formed another planet if they had not been jumbled by the effects of Jupiter's gravity. Most asteroids orbit within the belt; some, like Eros, Hidalgo and Adonis, travel unusual elongated paths.

sumably surrounded with a primordial atmosphere of "reducing" gases rich in hydrogen, such as ammonia and methane. At a later stage, large amounts of other gases, including water vapor and carbon dioxide, must have come out of its interior. Except for light hydrogen, no gases could simply escape into space, as the moon's gases did. Mars is so far from the sun that the top of its atmosphere probably does not get hot enough to accelerate the heavier molecules to the needed escape velocity. What, then, happened to the gases? Only carbon dioxide is still around in quantity and there must be some reason for the absence of the others.

A promising hypothesis to explain what became of the water vapor, at least, begins with a clue from Mariner IV. The spacecraft's instruments reported that Mars has no detectable magnetic field. It may therefore lack an iron core, which may mean that the iron in the material from which Mars was formed did not sink toward the planet's center. If the iron remained plentiful on and near the surface, it may have been the final cause of the water vapor's disappearance.

A surface of rust

In the first step of this process, water vapor in the atmosphere is separated by solar ultraviolet light into oxygen and hydrogen. The hydrogen released quickly escapes into space. In the next step the oxygen combines with iron, forming a rustlike compound. This takes oxygen out of the atmosphere and keeps it from accumulating there. Therefore the Martian atmosphere never acquired enough oxygen to shield its remaining water from decomposition by ultraviolet light, as is the case on the earth. With liquid water gone from the surface, water vapor would become scarce in the atmosphere, reducing its effectiveness for holding heat. Mars would therefore get colder and turn into what it is today, an almost frozen planet with no free oxygen and only a small, variable amount of water vapor above its surface.

The rust theory of Martian history is supported by observations. When sunlight is reflected from the surface of Mars, the light is altered in several ways by what it encounters there. The material found on the earth that alters light in the way that is most similar is limonite, an iron oxide chemically combined with water. It is dull orange-red and when finely pulverized has properties strikingly like the deserts of Mars.

The combined action of ultraviolet light and rusting iron may have been slow, so those who like to think that Mars was once more favorable for the appearance of life can look back hopefully to the youth of the planet. At that time it may have had a good deal of water on its surface and a climate warm enough to keep at least some water in the liquid state. If ammonia, methane and other reducing gases were present in its atmosphere, the stage would have been set, as it was on the earth, for the appearance of life.

Any kind of life that got a start on Mars would have slowly evolved by natural selection to keep up with changes in the environment. Life is enormously resourceful, and there is no reason to think that life origi-

nating on Mars would be less adaptable than the earth's. If free oxygen were never present in the atmosphere, life could thrive without it. Many of the earth's organisms do. If liquid water became scarce, Martian organisms might have come to retain a supply in their tissues and add to that precious hoard by acquiring other forms of water from the environment.

Many common earthly microorganisms can survive under Martian conditions. Scientists have put samples of soil in containers called "Mars jars," where the atmospheric temperature, composition, pressure and dryness are close to those of Mars. Some of the microorganisms in the samples always survive.

Insects with antifreeze

Living things are able to adapt themselves to extreme conditions. Many of the earth's microorganisms, for example, can withstand almost any degree of cold while they are in a dormant state. Some insects winter-proof themselves with glycerol, a common antifreeze used in automobile radiators. There is no conclusive reason why Martian organisms should not extend this principle, adding so much antifreeze to their tissues that they can live and reproduce in the extremely cold temperatures occurring on Mars.

More radical adaptations are possible, granted the origin of life on Mars and its subsequent evolution. If finely powdered limonite is a major constituent of Martian deserts, it may have become a medium of life. Each molecule of iron oxide in limonite is combined with about two water molecules. Any organisms that have found a way to extract water from limonite could live in the Martian deserts as if they were in oceans.

The possibility that Mars may support life is intensely interesting to scientists in fields outside astronomy. Many biologists feel that their science has potentially broader limits than the study of life on earth. On the biochemical level, all of the earth's multitudinous organisms have much more striking similarities than differences. All are believed to be descendants of a single remote ancestor whose basic chemistry they still retain. They all store the coded information that enables them to reproduce their species in large, coiled molecules of nucleic acid. They all use similar proteins (the enzymes) to promote and control the chemical processes that take place in their tissues. Not a single deviation from this general pattern has been found on the earth, though there are literally millions of closely related chemical compounds that might be used in the processes of life.

Why this curious narrowness? ask the biologists. They are eager to find out whether only one kind of life is possible or whether there may be others. Perhaps the earth's present type is the lone survivor of many less efficient kinds of life that appeared on the early earth and were eliminated by competition. Or perhaps it has survived and differentiated because it preempted the earth four billion years ago and created conditions that kept competitors from gaining a foothold. During that distant age,

A SPIDERLIKE MARTIAN, peering out of his space cylinder at an earthling in an illustration from H. G. Wells's *The War of the Worlds,* was the bizarre product of science wedded to fiction. Wells, writing in 1898, described his Martians as foundering under the strong gravitational pull of the earth, destroying everything in their path with a "heat ray" (a forerunner of the laser beam), and finally being wiped out by common bacteria, for which they had no defense.

the biologists muse, there must have come a critical time when only one example of the earth's kind of life was in existence. If this first ancestor —the original, primitive, microscopic Adam—had been killed by some misadventure, perhaps by an encounter with a cosmic ray, all organisms living on the modern earth might have had a different ancestor, different chemistry and different appearance and behavior.

The broad philosophical question of whether more than one kind of life is possible cannot be answered on the earth for a long time, if ever. Creation of complex forms of life in the laboratory appears to be far too difficult. But Mars may be a natural laboratory where life appeared billions of years ago and where descendants of those first organisms are still available for study. Only a few humble microorganisms need be found to provide a second example of life. If they have the same chemistry as life on earth, they will strengthen the view that only a single kind of life is possible. If they have some other chemical pattern, they will enlarge enormously the horizons of biology. Life will be proved to be a far-ranging influence that can mold nonliving matter in diverse independent ways, some of which may be suited to conditions widely different from the earth's.

"Rocks" that are alive

The discovery of life on Mars would be an event of profound significance, but the task of detecting it will not be easy. Orbiting cameras, however sharp-eyed, would almost certainly miss microorganisms that live below the surface. Even larger plants and animals (which may or may not exist) are likely to have forms or behavior that make them hard to recognize as alive. A rounded, limbless animal, for instance, that feeds on plants by very slowly moving over them would look like a lifeless rock in almost any kind of photograph.

Martian life may be confined to special places, microenvironments, where living conditions are unusually favorable. There is a good chance that water exists frozen under the surface; the red deserts may conceivably be frozen oceans covered with dust. Since Mars must be hotter inside, the ice should turn to liquid groundwater a moderate distance below the surface. If this is the case, any strong disturbance such as a volcanic eruption, meteorite impact or violent Marsquake may let water or water vapor escape, creating a moist "hot spot" especially suitable for life. An orbiting spacecraft equipped to measure temperature and water vapor might detect such microenvironments and give them close attention.

To determine the nature of Martian life would require landing an unmanned biological laboratory on the surface of the planet. It would need an apparatus to take samples of Martian "soil" and subject it to microscopic examination. It should be equipped for chemical analysis and biological culturing to see if anything in the soil samples can be made to grow. An elaborate computer could be programmed to watch for significant early findings and follow them up with appropriate experiments. The whole spacecraft would have to be carefully sterilized before it left

the earth so hitchhiking earthly microorganisms would not be taken as of Martian origin, and so none would get a chance to contaminate Mars.

Full understanding of Martian life may have to wait until human biologists have landed on the planet and have studied carefully the different microenvironments. This will be a formidable job. Though Mars is smaller than the earth, its lack of oceans gives it about the same land area. The terrain is extremely varied. Besides numerous craters, Mars probably has extensive highlands that may correspond to the earth's continents. Radar astronomy hints that their highest points may rise as much as 12 miles above the low-lying deserts, and the Mariner IV photographs show many mysterious markings that have not been identified. Mars will not be fully explored until all these topographical features—and others now unsuspected—have been investigated. No one can guess at present what is concealed among them.

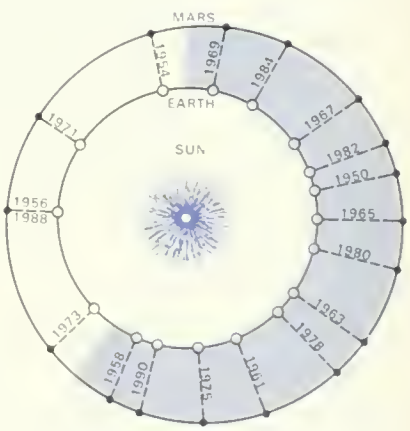
Exploration of Mars will surely include an investigation of its extraordinary satellites. There are two of them, Deimos and Phobos, and their small size and proximity to the planet make them unique in the solar system. Deimos is about three miles in diameter and about 15,000 miles from the surface of Mars. Phobos, five miles in diameter, is much closer (5,800 miles).

The most remarkable thing about Phobos, according to some observations, is that its period of revolution appears to be decreasing slowly but perceptibly. The only plausible explanation is that the slight drag of the Martian atmosphere is taking energy from it, thus making it move closer to Mars and follow a shorter and faster orbit. The Martian atmosphere is so thin that a satellite affected in this way must have extremely low density. If the observations are correct (which is not established), Phobos must be lighter than any known solid substance, even lighter than any natural porous material that could hold together.

The strange satellite of Mars

The Russian astronomer Iosif S. Shklovsky has supplied a novel answer to this puzzle. He believes that Phobos is hollow and artificial, the work of highly civilized Martians of hundreds of millions of years ago. When they decided that they would soon become extinct, his reasoning continues, they constructed one or two extraordinarily spacious satellites to serve as libraries and museums, and preserve for future explorers the glorious history and achievements of their doomed civilization.

Few scientists actually count on finding any such convenient repositories of ancient learning, and discovering any sort of intelligent, civilized life still flourishing is considered extremely unlikely. But explorers of Mars will certainly look for archeological evidence of long-dead civilizations. The beginning of life on a planet and its evolution toward higher forms has no fixed timetable. Life may have started early on Mars and evolved faster, reaching its civilized climax hundreds of millions of years ago. Even if nothing nearly as spectacular is found on Mars, the exploration of the planet will be an event unmatched in history.



OPPOSITIONS OF MARS, which occur every 780 days when the earth passes between Mars and the sun, provide the best periods for viewing the planet. Due to the different shapes of the planets' orbits, some oppositions *(light area)* are better for observation than others. The most favorable oppositions occur during the month of August at 15- or 17-year intervals, when the earth and Mars are closest together, within 35 million miles of each other.

The Changing Image of Mars

Through the centuries, Mars has stirred men's imaginations as has no other planet. To the ancients, its reddish glow was a celestial symbol of blood, and Mars was long personified as a god of war *(opposite)*. Persistent speculation that there might be intelligent beings on Mars reached extravagant proportions early in the 20th Century after American astronomer Percival Lowell interpreted the markings on Mars, seen by several astronomers, as canals that were the product of a culture far in advance of earth's. In the following years, an entire Martian civilization, complete with a capital city on Solis Lacus ("Sun Lake") sprang from a host of fertile imaginations.

Today, most astronomers believe that canals do not exist on Mars, at least in the form depicted by Lowell. Nevertheless, most think that there may be some life forms on the red planet. They point to a change on Mars in spring, when the surface shades turn darker, as a phenomenon that may be evidence of life. Even if this belief is incorrect, there may be organisms on Mars able to survive extreme cold, dryness and lack of oxygen, as some earthly organisms do.

THE SYMBOL OF WAR

Mars, shown as an armor-clad god of war in this 15th Century illustration, presides over the siege of an Italian city. The symbolic link between Mars and war was first made by the Sumerians in the Third Millennium B.C. and was continued by the Persians, Greeks and Romans. The astrological symbols of Scorpio and Aries mark the limit of the annual war-making time: March to October.

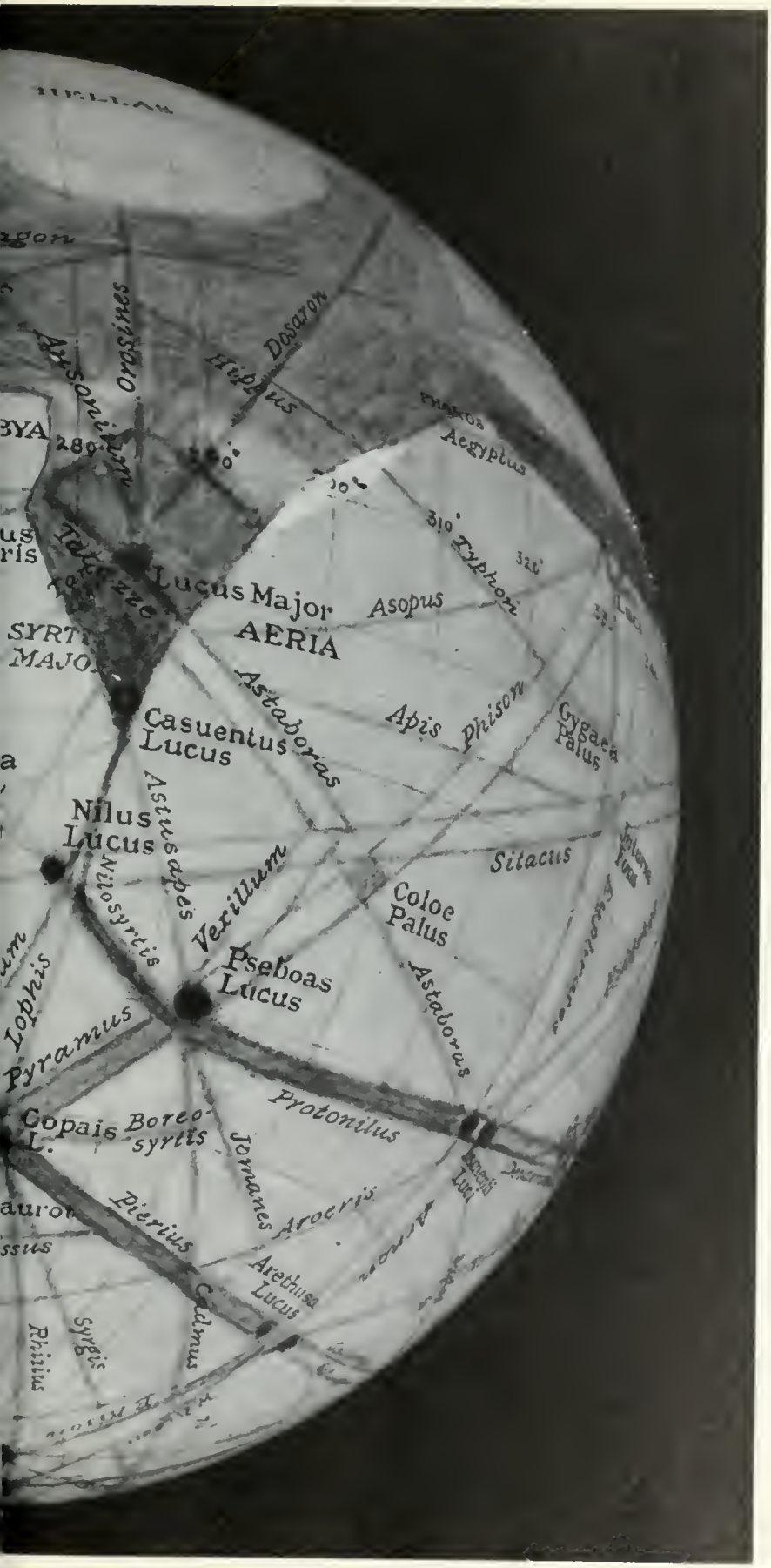
A Vision of Canals and Cities

The "discovery" of straight, geometrically patterned channels, or *canali*, on Mars by the Italian astronomer Giovanni Schiaparelli in 1877, and the subsequent conclusion by Percival Lowell that these were canals built by intelligent beings, touched off a controversy among astronomers at the turn of the century. Many, like the U.S.'s Edward E. Barnard, stoutly denied that any such lines even existed and implied that they were the result of overactive imaginations. Some claimed the *canali* were optical illusions that disintegrated into short, disconnected features when viewed during the clearest periods.

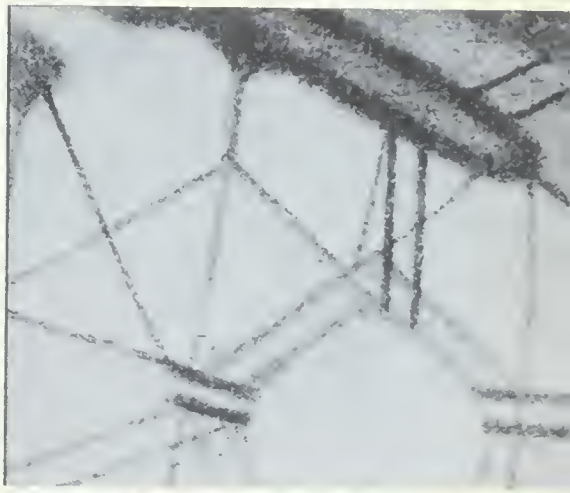
Most modern astronomers tend to dismiss Lowell's elaborate map of Martian canals *(opposite)*. They admit there may be lines on Mars *(page 145)*, but if so they probably mark ancient fractures in the crust or long rows of wind-whipped sand dunes.

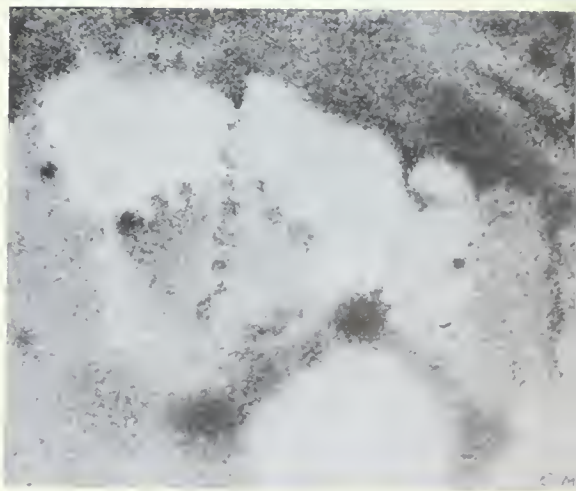
A WORLD FROM A BLUR

The drawing above, by Giovanni Schiaparelli, reveals the vaguely defined lines he thought were of geologic origin, like the English Channel. Percival Lowell, using Schiaparelli's information and his place names, drew the 1903 map *(right)* which shows a complex of canals—some as wide as 50 miles—radiating out from oases and polar caps to connect Martian cities.



VENICE ON MARS
A lofty, glass-domed city, served by great waterways, is shown in this illustration of Lowell's concept. It was taken from a Russian film that discussed Lowell's hypothesis, as well as others.





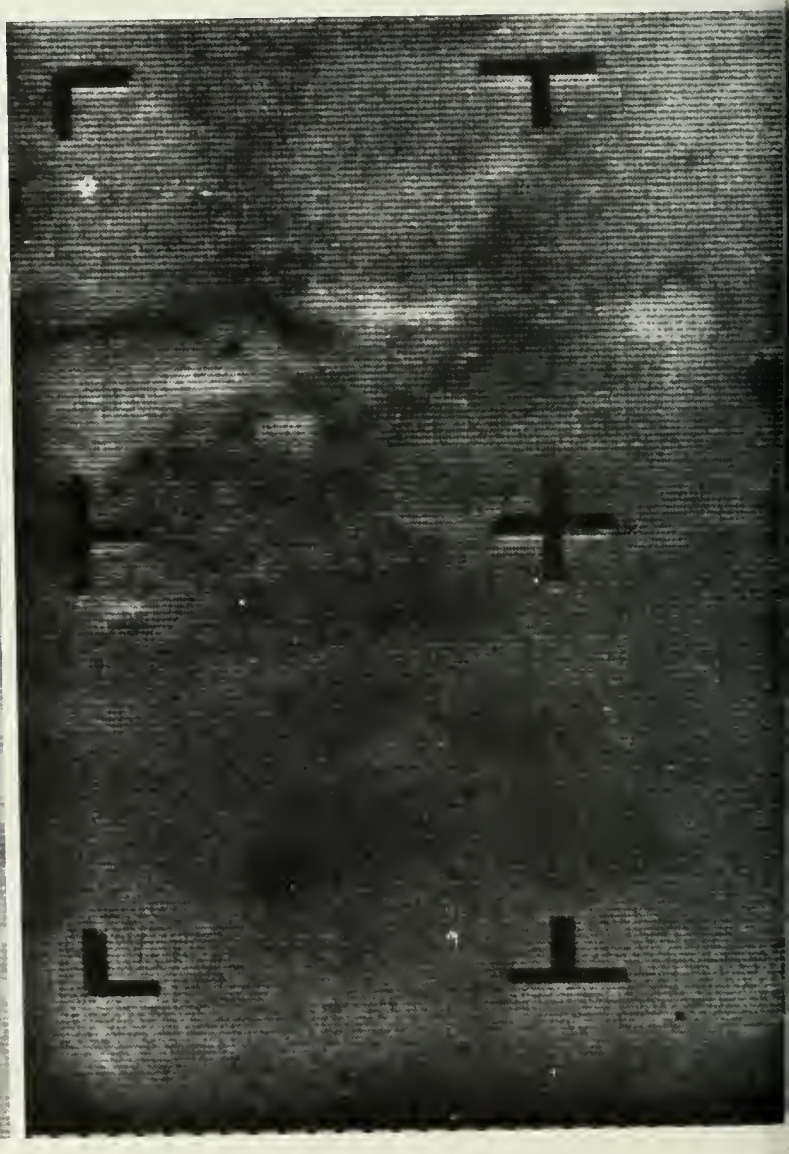
TWO VIEWS OF THE "CANALS"
The Schiaparelli map *(top)* shows a pattern of *canali*, many of them parallel, he described as being like "the finest thread of a spider's web." But astronomer Eugenios M. Antoniadi drew a different picture *(bottom)* after viewing the same area in moments of exceptional clarity. He saw indistinct patterns, the *canali* having dissolved into disjointed smudges on the surface.

The Closest Look at Mars

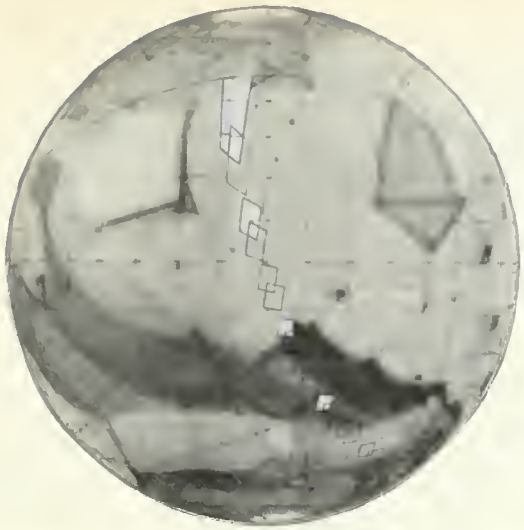
The real face of Mars, a far different sight than any ever seen from earth, was dramatically disclosed by the United States satellite Mariner IV in 1965. After a trip of more than seven months and 325 million miles, Mariner IV passed within 6,100 miles of Mars and relayed to earth a series of 22 remarkable photographs, four of which are reproduced below.

A painstaking examination of the pictures produced surprises. One is the presence of barely discernible straight lines *(far right)*, which possibly delineate a Lowellian canal. Another is the number of Martian craters. Within the 1 per cent of the Martian surface covered by the pictures *(right)* are some 70 craters, ranging from three to 75 miles in diameter. This indicates that the entire planet contains about 10,000 craters—as compared to fewer than 200 known craters on earth. Considering the planet's proximity to the asteroid belt, astronomers might have expected to find many more craters than the pictures show. Telltale signs of weathering on some of the craters seem to indicate that significant erosion is taking place, and that water or wind wore away the older craters.

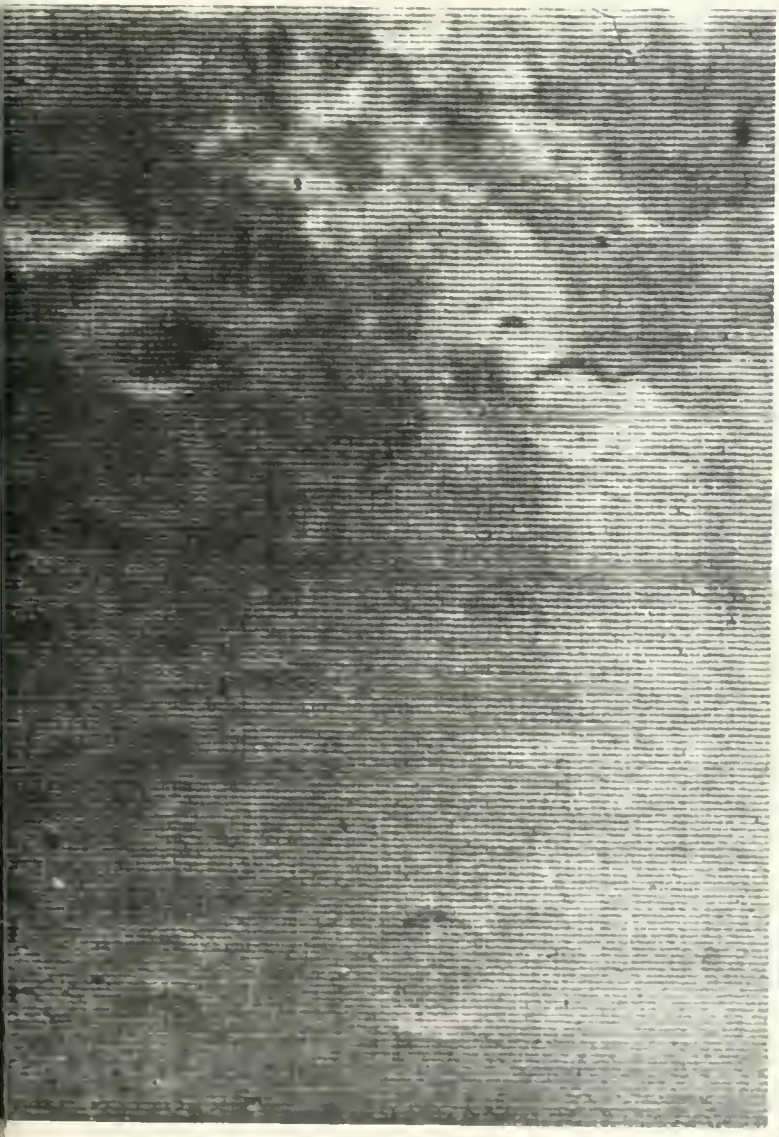
1 ZEROING IN ON MARS
The first photograph in the Mariner IV series shows the horizon of Mars and a whitish cover which some astronomers believe is formed by clouds floating high in the Martian atmosphere. The dark line below the horizon has not been explained.



2 THE DISPUTED CLUE
A branching pattern in the upper left corner of this photograph can be observed by careful examination. This has been interpreted by some scientists as either a flow system of an unidentified material, possibly water, or as depressions in the surface.

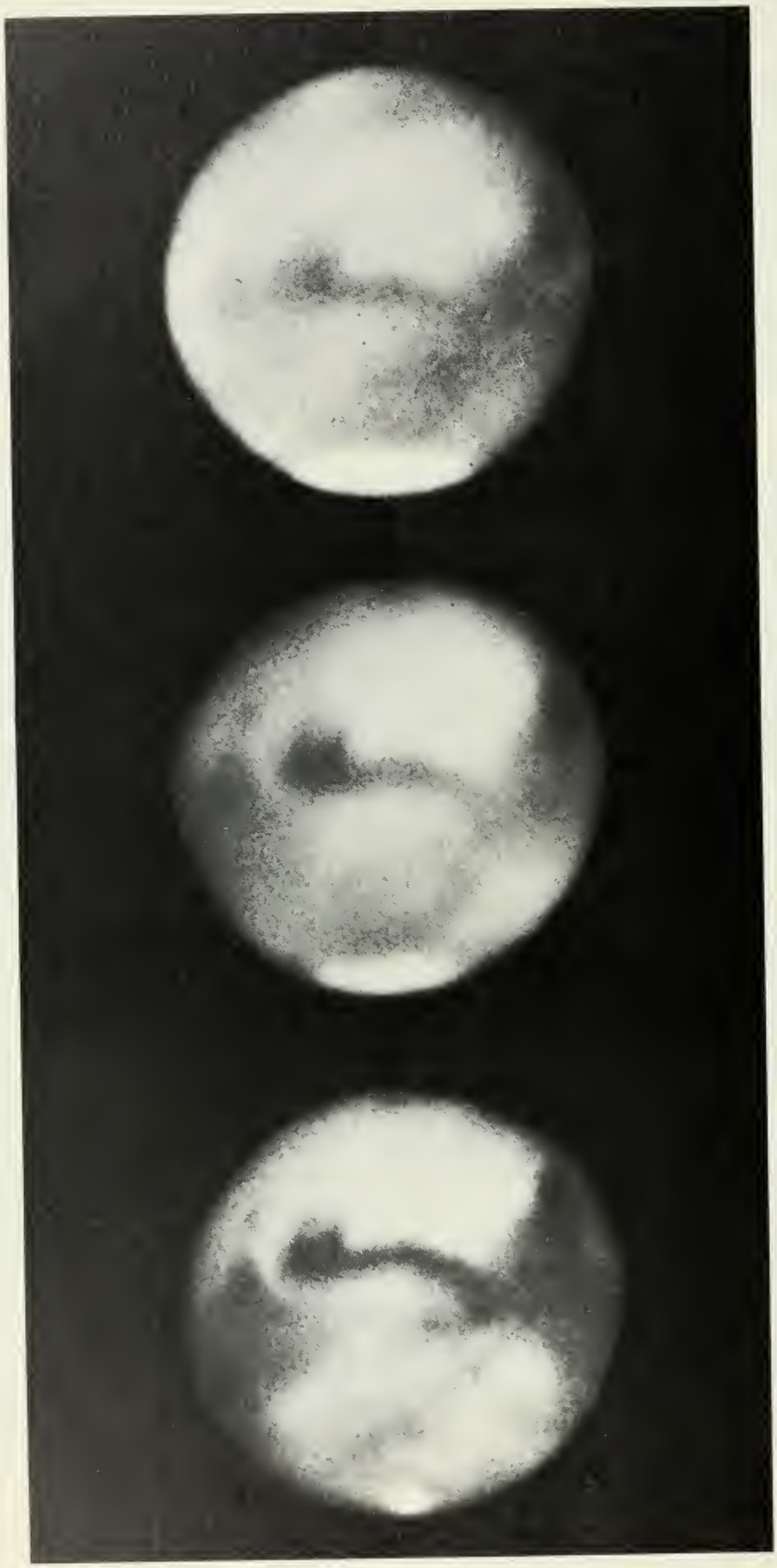


THE PATH OF MARINER IV
Superimposed on a map of Mars are 22 areas, each representing a region covered by a Mariner photograph. The shaded rectangles indicate the pictures below. The one at the right below, No. 11 in the series, has been called one of the most remarkable scientific photographs ever made, because it shows distinct craters, possible flow patterns and even straight lines



3 FROM LIGHT TO DARK
The surface of Mars has both light and dark areas, as shown here. Observers have noted the presence of many more craters in the dark areas than in the light, where dust has probably filled the older craters, blending them into the Martian surface

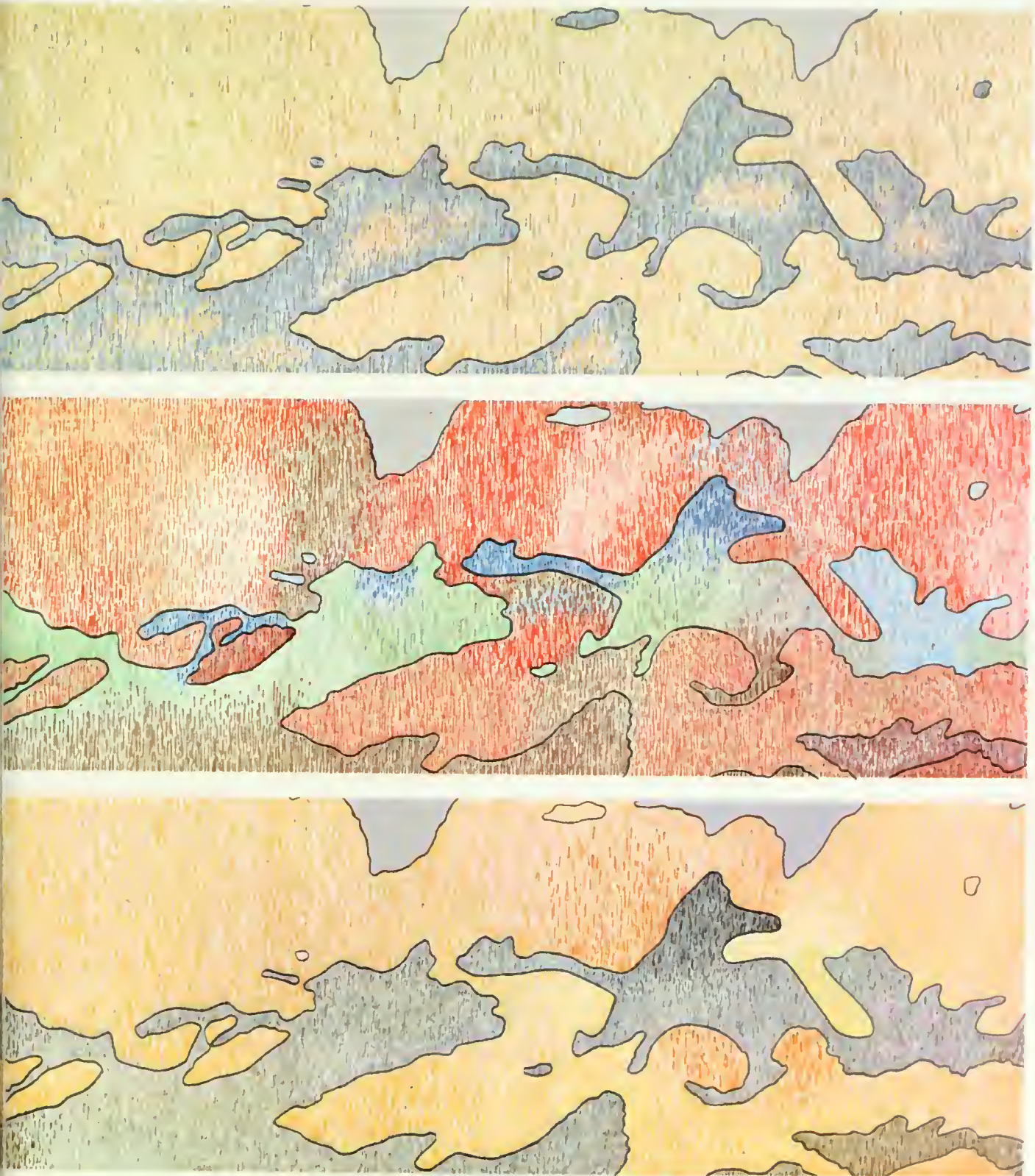
4 LINES OR CANALS?
The presence of two barely perceptible straight lines in this photograph surprised most astronomers. Some believe both may be surface fractures and have estimated the clearer one *(solid line)* to be five miles wide and more than 150 miles long



Three Faces of Mars

One thing on which all astronomers agree is that they can see Mars undergoing definite seasonal changes. As winter turns to spring, the polar frost cap recedes and a wave of darkening spreads from the pole toward the equatorial belt, as the three telescopic photographs at left illustrate. But what conclusions can be drawn from this phenomenon remains a matter of dispute. Some astronomers see the darkening landscape as evidence of awakening life: tiny organisms consuming water vapor released by the melting frost. Others insist that the Martian spring reveals nothing about life; the areas of darkness may be caused solely by seasonal winds which redistribute the fine particles of dust. Such problems of interpretation cannot be resolved so long as astronomers are restricted to their present equipment and techniques. Even a uniform description of Mars's springtime colors is difficult, as can be judged from the maps at the right.

SPRING COMES TO MARS
Three photographs trace the changes on the surface of Mars from late winter *(top)* through spring *(center)* and into early summer *(bottom)*. The polar frost cap can be seen as a shrinking circle at the bottom of each picture, while the dark areas become much more pronounced.

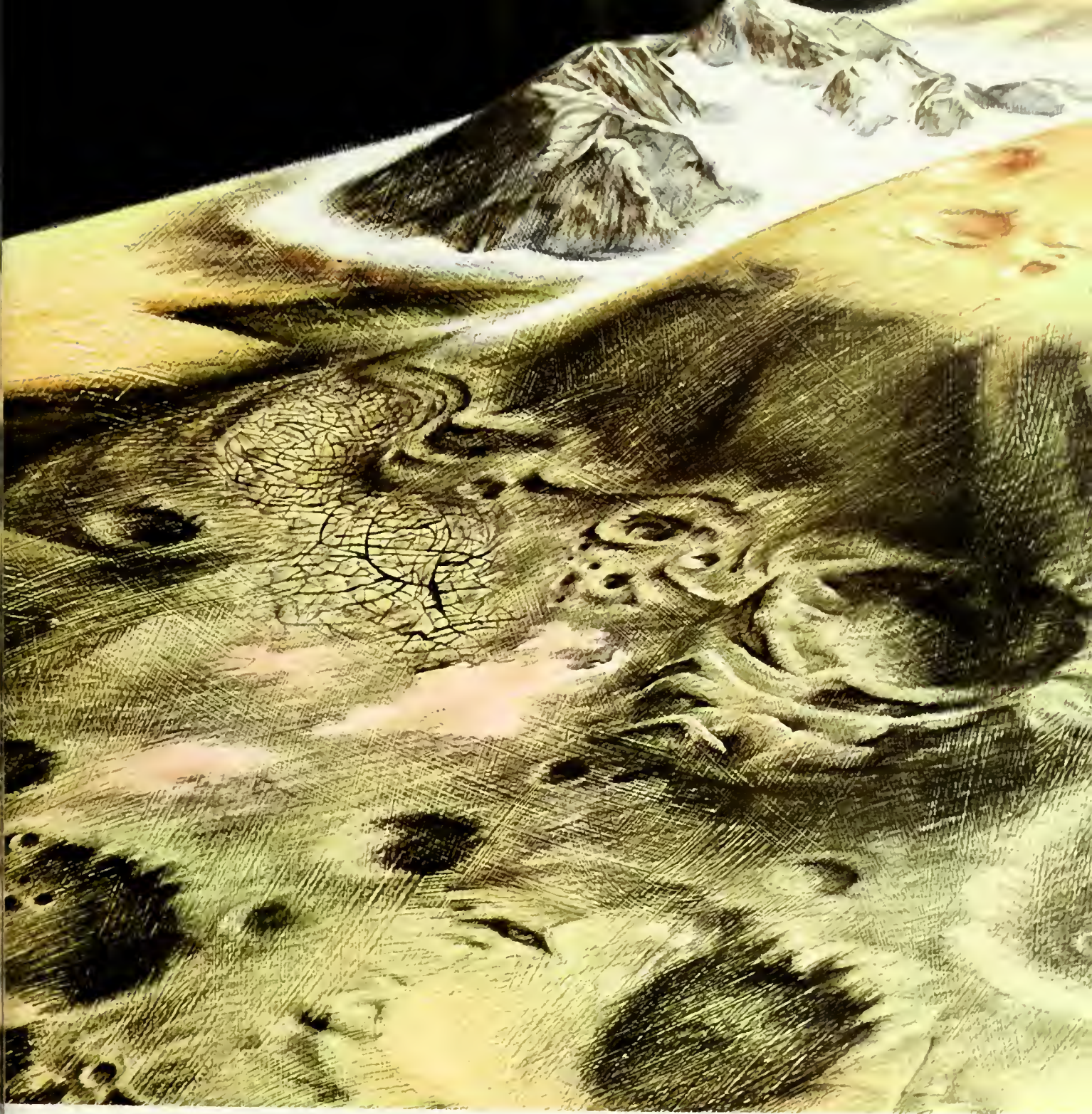


THE COLORS OF SPRING

The difficulty in rendering the changing hues of a Martian spring is attested by these three maps of Mars's southern hemisphere, colored from descriptions given by three different astronomers: Percival Lowell *(top)*, Eugenios M. Antoniadi *(center)* and Gerard P. Kuiper *(bottom)*. Such varying views show the tricks that Mars can play even on highly trained eyes. The human eye is an imperfect and unreliable instrument when it sees colors. It frequently attributes spurious color to a neutral area that is next to a bright one. In addition, the colors the astronomer sees may be distorted by the glass of his lens. Scientists now believe that the top two versions are inaccurate. But Kuiper, who used a different viewing technique, is close to the present consensus: burnt orange and gray, with some traces of brown and green.

Signs of Life on Mars

Many astronomers believe the changing tones that mark springtime on Mars may mean that life exists there. Just as sprouting plants provide the green color of spring on earth, tiny organisms, perhaps the size of algae, are thought to be responsible for the darkening that characterizes the Martian season. According to this concept, the organisms live just beneath the dusty surface. In the frigid winter they hibernate, using the water stored in their systems. But during the spring thaw, these organisms can absorb water from the surface or "drink" water vapor from the atmosphere. It is the mass movement toward the surface, where the organ-



isms grow and multiply, that is said to cause the visible darkening.

This rendering of spring in a Martian polar region combines several biological hypotheses. The dark gray-green areas are the inhabited lowlands. Moisture comes from the frost-covered peaks at upper right (in this view the frost is heaviest on the lower slopes, but other concepts place the thickest cover higher up). The frost yields water vapor to a spreading darker zone, in effect a breeding ground for colonies of the organisms (pink shading). A dry riverbed indicates that water has flowed on Mars, and a different form of aquatic life may exist in nearby brackish pools.

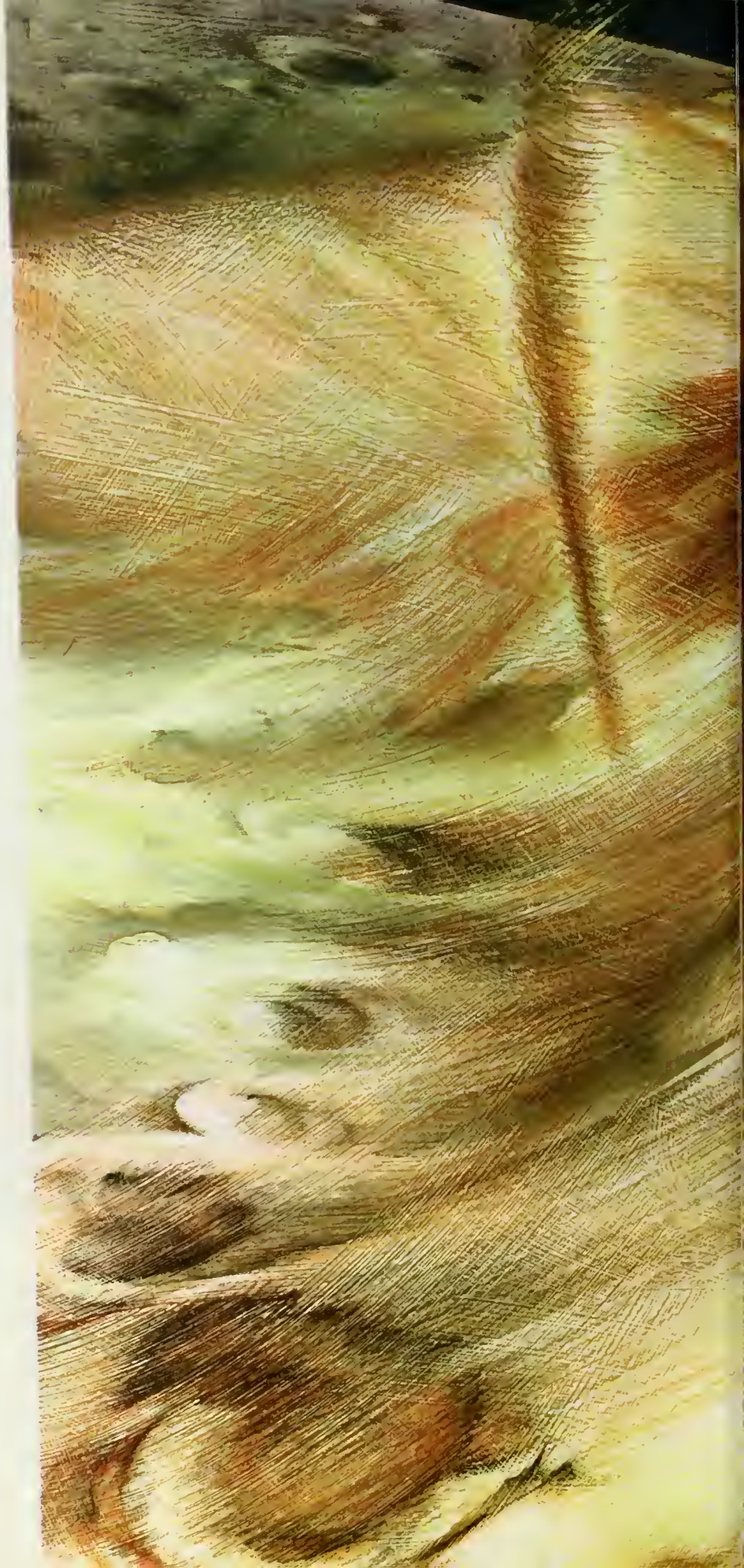
A Windswept Wasteland

A Martian spring has another explanation, according to some astronomers. They theorize that the springtime contrasts are the result of nothing more than wind sweeping fine specks of dust off the plateaus and into the lowlands. Because the larger particles remaining on the plateaus reflect less light, they appear darker to the observer on earth. In the fall, the wind pattern is said to reverse, blowing the smaller particles back onto the plateaus and restoring the contrasts upon the Martian surface once more.

Even though the seasonal changes are not due to life in this theory, there still may be life present that cannot be seen.

The gray-green plateaus are studded with craters eroded by wind—but not rain. Clouds of dust swirl through the valley, occasionally twisting into a tornadolike dust devil *(upper left)*.

But not until scientists can get a closeup look will it be possible to make a more conclusive assessment of whether Mars is or is not a planet harboring life. This will be the main objective of Project Voyager, the United States' effort to land an unmanned laboratory on Mars in 1973.



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A Strange Veiled Giant

Galileo's words and sketches record his discovery of four of Jupiter's satellites in 1610.

JUPITER, THE BIGGEST PLANET, is also the liveliest. It rotates in less than 10 hours, faster than any other planet. Its markings sweep across its face in a single evening, and a sharp eye at a good telescope can see distinct changes in a few minutes. It is hard to remember while watching these rapid motions how enormous Jupiter is. If Mars were placed on the face of Jupiter, it would look like a dime on a dinner plate. Jupiter has more than 11 times the earth's diameter, 300 times the mass and 1,000 times the volume. It has 12 satellites, more than any other planet, and it contains twice as much matter as all the other planets put together. In some respects it may behave more like a star than a planet of the solar system.

Jupiter is not only big but bizarre, full of violence, mysteries and surprises. Its highest clouds are chiefly ammonia snowflakes. Its turbulent atmosphere reaches thousands of miles deep, so deep that no one knows where it ends. In nearly every way Jupiter is utterly unlike the earth. Its extreme temperatures, its prodigious pressures and its atmosphere poisonous to man would seem to make it uninhabitable, but this negative judgment is now known to be unjustified. Recent work on the origin of life and the environment of Jupiter suggests that it may be more favorable to life than any other planet, not excepting the earth.

The first step toward understanding Jupiter is to note that although its mass is enormous, the planet is not dense. In fact, its density is remarkably low, only 1.33 times that of water. The earth is about 4.1 times as dense, about like iron ore. The surprisingly low density of Jupiter is the key to its composition. There is only one substance that could keep such low density despite the compression of Jupiter's powerful gravitation, and that substance is hydrogen, the lightest of all the elements. If it were mixed with 10 per cent or so of helium, the second-lightest element, the combination under compression would approximate the density of Jupiter. Heavier elements such as those that make up most of the earth cannot be present in large proportions. Spectroscopic and other evidence supports this conclusion by showing that the atmosphere of Jupiter is indeed largely hydrogen and helium.

The hydrogen-helium combination has a clear meaning for astronomers. These light gases are comparatively rare on the earth, but they are by far the commonest elements in the stars and interstellar matter that form the bulk of the universe. Their abundance in Jupiter shows that the planet has changed comparatively little in composition since the solar system condensed out of interstellar gas and dust five billion years ago. In Jupiter's central core or mixed throughout its interior may be enough iron, silicon and other heavy elements to make a dense planet about the size of the earth, but these materials are overwhelmed by hydrogen and helium. As a result, Jupiter is more like the sun in composition than it is like the earth.

While all planets were probably formed initially from a hydrogen-rich mixture of gases, the earth and its near neighbors have lost almost all of their initial atmospheres. Jupiter has retained hydrogen and helium be-

cause of its large gravitation and its distance from the sun. In its remote orbit, 486 million miles from the sun, sunlight is only 1/27 as strong as it is on the earth. The planet's outer atmosphere is so cold that hardly any hydrogen molecules get moving fast enough to escape from the powerful gravitation. But if the sun ever grows much brighter, as astronomers believe it eventually will, Jupiter's exterior temperature may rise enough to permit the departure of first hydrogen, then helium. If this happens, the planet will shrink to a small, dense globe of heavy elements, somewhat like the earth.

The knowledge that Jupiter's huge mass is composed almost entirely of hydrogen and helium gives astronomers something to start with in devising a model of the planet. Even the comparatively light atmospheric gases of Jupiter are powerfully compressed by their own weight, because the great gravitation—at cloud-top level it is 2.6 times as strong as the earth's—makes everything correspondingly heavy. A few thousand miles below the visible cloud deck the pressure is so enormous that the hydrogen becomes thick, and at some point farther down it probably turns to a kind of solid. Whether Jupiter has a sharply defined surface is uncertain. The main mass of solid hydrogen may be covered with a slush composed of fluid hydrogen mixed with particles of materials that solidify more readily than hydrogen does.

Where hydrogen becomes a metal

Even farther down, no one knows just how far, an extraordinary change is believed to take place as the hydrogen is subjected to tremendous compression. When pressure rises above a million earth atmospheres (one atmosphere equals 14.7 pounds per square inch), hydrogen atoms are crushed in such a way that their electrons are separated from their nuclei. In this state hydrogen behaves like a metal. It is denser than normal solid hydrogen and like most metals is a good conductor of electricity. Jupiter's core is believed to be made of this strange stuff—a metallic version of an element known on earth as the lightest of all gases.

Jupiter's atmosphere is as remarkable as its core. The surface of the clouds—which is all that is visible of the planet—has been studied for centuries. Even a small telescope shows the numerous, quickly changing markings that make Jupiter unique. Parallel to its equator, covering most of the surface, run alternate bright and dark bands. About 10 are generally visible, but 14 appear often enough to have been named. Dark bands are called "belts," while bright bands are "zones," such as the "North Tropical Zone." The belts and zones continually shift, merge, fade, grow wider or narrower. Bright or dark patches appear suddenly in them, spread out into streaks and disappear.

Astronomers had hardly begun to study Jupiter when they found that its visible surface does not rotate as a unit. The bands within 10 degrees of the equator complete a rotation about five minutes faster than the bands to the south and north of them, one group racing past the other at about 220 mph. These racing parallel bands are easy to explain in a

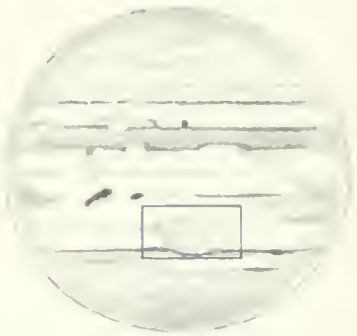
general way; the earth has something like them. The earth's trade winds, which blow from east to west, and its prevailing westerlies, which blow from west to east, are currents of air originally set in motion by the solar heating at the equator. On a nonrotating earth, some of these currents would blow northward and others southward, but the earth's rotation turns them into west or east winds. If these currents could be identified by the color of their clouds and were not disturbed by ground topography, they would look from space rather like Jupiter's bands. Since Jupiter is much bigger than the earth, it would be only natural that it should have more "trade winds" and "prevailing westerlies" than the earth has.

Except for these east-west currents, the atmosphere of Jupiter does not resemble the earth's. It has no detectable oxygen or nitrogen, the gases that make up the bulk of the earth's atmosphere, but spectroscopy has determined that it has ammonia and methane along with the predominant hydrogen and helium. Scientists infer that water vapor is also present. They reason that an assortment of elements typical of the universe at large contains oxygen, and on Jupiter it must have combined with hydrogen to form water.

Snow and rain made of ammonia

The conspicuous clouds in Jupiter's bright bands are probably not composed of water. These are indicated by spectroscopic evidence and temperature measurements to be ammonia crystals hanging high in the atmosphere, where the pressure is about five times the earth's at sea level and the temperature is low enough to keep solid ammonia from evaporating. Below the ammonia crystal clouds are probably clouds of liquid ammonia droplets. Still farther down, water vapor condenses as ice crystals, and below that water droplets. All these crystals and droplets fall, so Jupiter must have ammonia snow and ammonia rain, and water snow and water rain. None of this precipitation falls very far; it evaporates a little below the clouds and the vapor is carried up to the clouds again. This meteorological turmoil, which is much more violent than any weather on the earth, is almost certainly accompanied by enormous electrical discharges that would make earthly strokes of lightning look like harmless sparks.

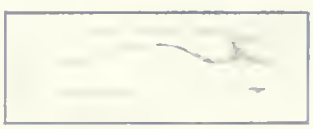
In the midst of this maelstrom stands the most stable—and perhaps the most unusual—visible feature on Jupiter: the Great Red Spot. It is a long oval area, set into the South Tropical Zone at a latitude equivalent to Rio de Janeiro on earth. Its size has varied somewhat but it is usually 8,000 miles broad and 25,000 miles long, which is more than three times the earth's diameter. The color of the Spot varies; it is sometimes brick red, sometimes dull pink, sometimes gray. It has a rotational speed of its own, moving four and a half miles per hour slower than the brighter material around it. Sometimes it seems to disappear entirely, showing its presence by an indentation, the Red Spot Hollow, in the adjacent South Equatorial Belt.



JUPITER'S GREAT RED SPOT *(in box above)* is its most prominent feature. Although its erratic movements and changing shape and color *(below)* have been observed since the 19th Century, there still is no completely satisfactory theory to account for its origin. Astronomers are not even sure what gives it its color, although both visual and spectroscopic observations have proven that the Great Red Spot is indeed red much of the time.

1882

1921



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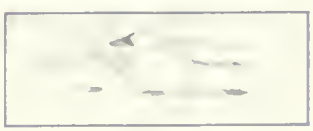


1938

What this gigantic discoloration might be has puzzled astronomers for centuries. Until recently the Spot was considered some sort of solid object floating in the dense lower atmosphere and showing its upper surface above the clouds. One objection to this explanation is that no known solid substance is light enough to float in the hydrogen-rich atmosphere of Jupiter no matter how strongly compressed. Another is that any free-floating body subjected to the rotational forces of rapidly spinning Jupiter would drift toward the equator, and in 300 years the Great Red Spot has shown no sign of such drifting.

The most widely accepted modern theory holds that the Spot is caused by a topographical feature, either a rise or a depression, on Jupiter's solid hydrogen "surface." The feature must be very large, but it need be no more than a few miles high or deep. Influenced by the planet's rotation, the dense atmosphere flows around the feature, and generates a column of relatively stagnant gas—called a Taylor column—that extends upward. The column reaches through the tops of the bright ammonia clouds, where it shows as the Great Red Spot.

The origin of the topographical feature that apparently causes the Great Red Spot is not known, but there are several promising possibilities. Jupiter's interior may be in motion like the earth's mantle, wrinkling the surface into mountain ranges of solid hydrogen, one of which is big enough to cause the Spot. Another possibility is that something outside Jupiter—such as a large comet or asteroid—may have scarred the surface. Or perhaps a heat source below the surface turns large amounts of solid hydrogen to gas, thus creating a depression big enough to support a Taylor column.

The planet that acts like a star

Jupiter does seem to be generating some heat of its own. Delicate recent measurements of its temperature suggest that it gives off about twice as much energy as it acquires from the sun. It may, indeed, be acting as an exceedingly feeble star. The sun was once feeble, too. When it began to form out of a thin cloud of interstellar gas and dust, its center was comparatively cool, but as it collected more material from outside, its mass increased and so did the strength of its gravitation. The increased pull made the great ball of gas contract, and the contraction (equivalent to falling toward the center) released gravitational energy that turned into heat. Not until the sun's center reached the temperature of many millions of degrees did thermonuclear reactions start and make it shine as a true star.

Since Jupiter's interior is not hot enough to sustain the thermonuclear reactions that power full-grown stars like the sun, the most likely source of its excess heat energy is contraction. Jupiter may be shrinking as the sun once did, its material falling slowly toward the center and releasing gravitational energy that appears as heat. In some unknown manner the heat works its way to the surface, where it stirs the atmosphere to turbulence and motion and makes it radiate into space a little more energy

than it receives from the sun.

Not all astronomers accept this chain of reasoning. The heat that appears to flow from Jupiter's interior may be due to other causes. In any case, Jupiter is not a real star, and is not likely to get much hotter. But if its mass were five to 10 times greater, its increased gravitation would make it shrink to smaller size, and its center would get hot enough for thermonuclear reactions to start. Then Jupiter would shine with its own light as a "red dwarf" star, and the sun would be a double star like billions of others in the sky.

Jupiter's big surprise

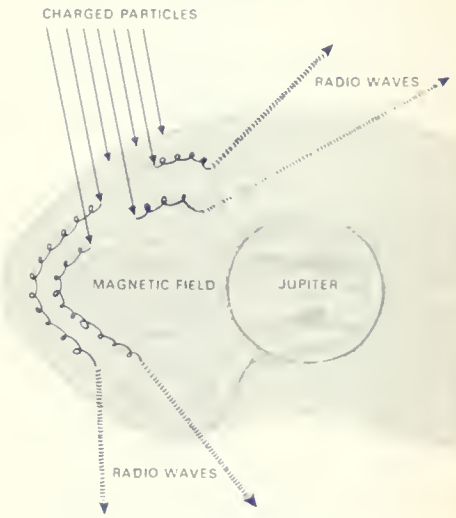
Whether Jupiter is an undersized star or an oversized planet, it behaves in remarkable ways, not the least surprising of which is its extraordinary activity in broadcasting radio waves. In 1955, when radio astronomy was still comparatively new, a telescope near Washington, D.C., was searching the sky for small new radio sources. The telescope picked up strong 22.2 megacycle (13.5 meter) waves that were at first attributed to ground interference such as automobiles with faulty ignition systems. The interference persisted, and although Jupiter was shining bright and high overhead at the time, none of the astronomers thought for several months to blame it for the mysterious waves. At that time planets were not considered promising radio sources.

But the astronomers persisted and, to their great surprise, found that the source moved against the background of stars in a way that showed it must be Jupiter, which proved to be one of the strongest radio sources in the sky. Some of the waves have been traced to their origin on the planet; others are still mysterious, and the intricate puzzle they present makes Jupiter a favorite subject for radio astronomers.

The shortest of them, less than one inch long, come from above the clouds of Jupiter and give a temperature of −220° F., which is close to the temperatures obtained from infrared studies. The slightly longer microwaves from Jupiter cannot come from the atmosphere or clouds, which would have to be absurdly hot to emit them as strongly as observed. Radio telescopes have shown that they originate in a huge region around Jupiter—a region 3.5 times the planet's diameter and completely outside the planet itself.

This finding confirmed an earlier suspicion that the microwaves must be generated by a gigantic belt that is analogous to the earth's Van Allen belts but is much, much larger. The particles themselves come from the sun, and they can be trapped in the belt only by a magnetic field. If Jupiter has a magnetic field, it would presumably arise from the electrically conducting core of metallic hydrogen, which would generate magnetism in somewhat the same way as the earth's core of metallic iron. No other planets are known to be like this. Neither Venus nor Mars nor the moon exhibits detectable magnetism, and this lack has been taken to mean that none of them possesses metal cores.

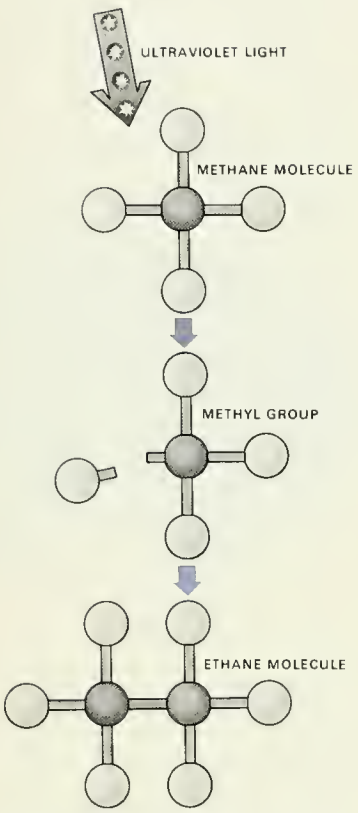
The microwaves from Jupiter, informative though they may be, are



RADIO WAVES FROM JUPITER puzzled astronomers until radio telescopes revealed that they were not emitted by the planet itself but by particles trapped in its magnetic field *(elongated circles)*. In a process analogous to the formation of the earth's Van Allen belts, charged particles from the sun *(arrows)* are trapped by Jupiter's magnetism. They then spiral around the planet, radiating waves directly in front of them that are powerful enough to be detected by receivers on earth, about 400 million miles distant from Jupiter.

not really so spectacular as the planet's longer, decameter waves. These waves, between 25 and 200 feet long, are almost incredibly powerful. They come in "bursts" and "storms," the bursts lasting anywhere from one thousandth of a second to several seconds and the storms—each made up of a great many bursts—lasting as long as two hours. A single one-second burst releases radio waves equivalent in energy to those generated by 100 billion earthly strokes of lightning. During a storm these enormous bursts follow one another in staccato succession, giving Jupiter a radio voice that must reach far beyond the solar system.

The powerful and capricious decameter waves baffled radio astronomers for quite a while. Their origin still is not entirely clear, but they are believed to come from charged particles of exceptionally high energy in Jupiter's belt. If these energetic particles stayed in the belt and circulated there in an orderly manner, they would not generate the tremendous bursts of decameter waves. But, like most things on Jupiter, they do not remain orderly. At irregular intervals great swarms of them plunge from the belt and down to the top of Jupiter's atmosphere, where they stop suddenly and expend part of their energy as radio waves. Scientists call this "dumping." Something similar happens when high-speed particles leave the earth's radiation belts and hit its atmosphere near the magnetic poles, causing the aurora, including the familiar northern lights. The frequent flickering of the aurora can be compared to the quickly repeated bursts of Jupiter's decameter waves.



ORGANIC MOLECULES on Jupiter may be formed by a sequence like the one shown here. When ultraviolet light *(top)* charges a methane molecule with energy, one of its four hydrogen atoms is snapped off and the molecule becomes a methyl group. Two such groups can then join to form a complex molecule, ethane *(bottom)*. Astronomers believe that similar reactions on Jupiter have produced even more complex molecules which may account for the bright colors of the planet's clouds, and may even have provided the basis for some form of life there.

Triggering the radio storms

It is not perfectly understood why Jupiter's storms of radio bursts should come at such irregular intervals. There are probably several triggering mechanisms that cause this dumping, but only one of them has been discovered so far. Storms of decameter waves are unusually frequent when Jupiter's nearest major satellite, Io, is at certain positions on its orbit, suggesting that the satellite triggers them. How does Io do this? A hint that may lead to a full explanation lies in the fact that the earth's moon leaves a sort of magnetic wake behind it. As the moon moves in its orbit, it sweeps up charged particles from the sun. Io is about as big as the moon, and its orbit carries it through Jupiter's magnetic field. It may somehow interfere with the free movement of the charged particles that are circulating there and cause them to be dumped into Jupiter's atmosphere.

Many mysteries still remain about Jupiter's radio waves. They seem to be almost as complicated as the sound waves emitted by an orchestra, and they are obviously full of hidden meanings. When they have been decoded they should answer many questions about giant Jupiter. They may tell, for instance, what parts of Jupiter have temperatures suitable for living organisms.

It might seem preposterous to suggest that life could survive on such a hostile planet, but Jupiter may be a good place for some forms of life to develop and evolve. In fact, conditions on present-day Jupiter are not

very far from those that apparently did produce life on the earth some four billion years ago.

When the earth was first formed, its primordial atmosphere may not have been as extensive as Jupiter's, but it is believed to have contained the same essential gases. These are hydrogen, water vapor, ammonia and methane. All these gases are present in the atmosphere of Jupiter and it almost surely contains enough of the other elements—such as iron and phosphorus—that earthly life needs in small amounts.

The only other requirement for the appearance of complex organic compounds that are the precursors of life is a source of energy to break up simple molecules such as water and methane so that their fragments can join together. In the case of the earth, this energy source was probably ultraviolet light from the sun. If the sunlight on Jupiter is not sufficient, that planet probably has another source of energy: powerful lightning flashes in its turbulent and cloudy atmosphere. Laboratory experiments have proved that electric sparks—and strokes of lightning are nothing but large sparks—discharged through Jupiterlike mixtures of gases can produce complex organic molecules.

Where life might be found

Life could hardly begin in the tops of Jupiter's clouds, which are probably too cold, or in the bottom of its atmosphere, which is certainly too hot. But between the extremes there must be levels where water exists as liquid droplets. This is Jupiter's potential "life zone." Some adverse circumstances may have kept it free of life, but there is a chance that during the five billion years of Jupiter's existence a combination of organic molecules may have acquired the critical ability to reproduce itself and evolve to higher forms.

That at least a part of this process has taken place is suggested by the positive colors of Jupiter's wind bands and of its Great Red Spot. The gases known to be abundant in Jupiter's atmosphere are essentially colorless, and the only colored molecules that they can form are organic. Life and its chemical precursors can have any color, from the green of a leaf to the red of blood. Great telescopes of the future, floating in space, may prove that Jupiter's Great Red Spot, like the earth's Red Sea, gets its color from complex organic compounds.

If life has evolved on Jupiter, it will not be like familiar earthly life. Its basic chemistry may be wholly different, and in any case it will not breathe free oxygen because Jupiter's atmosphere has none. Since no solid surface is accessible, the organisms will have to float and, if large, they will have to be living balloons floating in gas. Most of them probably will be microscopic, but a few of them could be fairly large and could be equipped with some sort of propulsion to take them to their food. The chance that they will be intelligent is not considered good, but if life of any kind is found on Jupiter, it will show that life is possible on planets unlike the modern earth. It will strengthen the growing belief that life is a normal phenomenon throughout the universe.

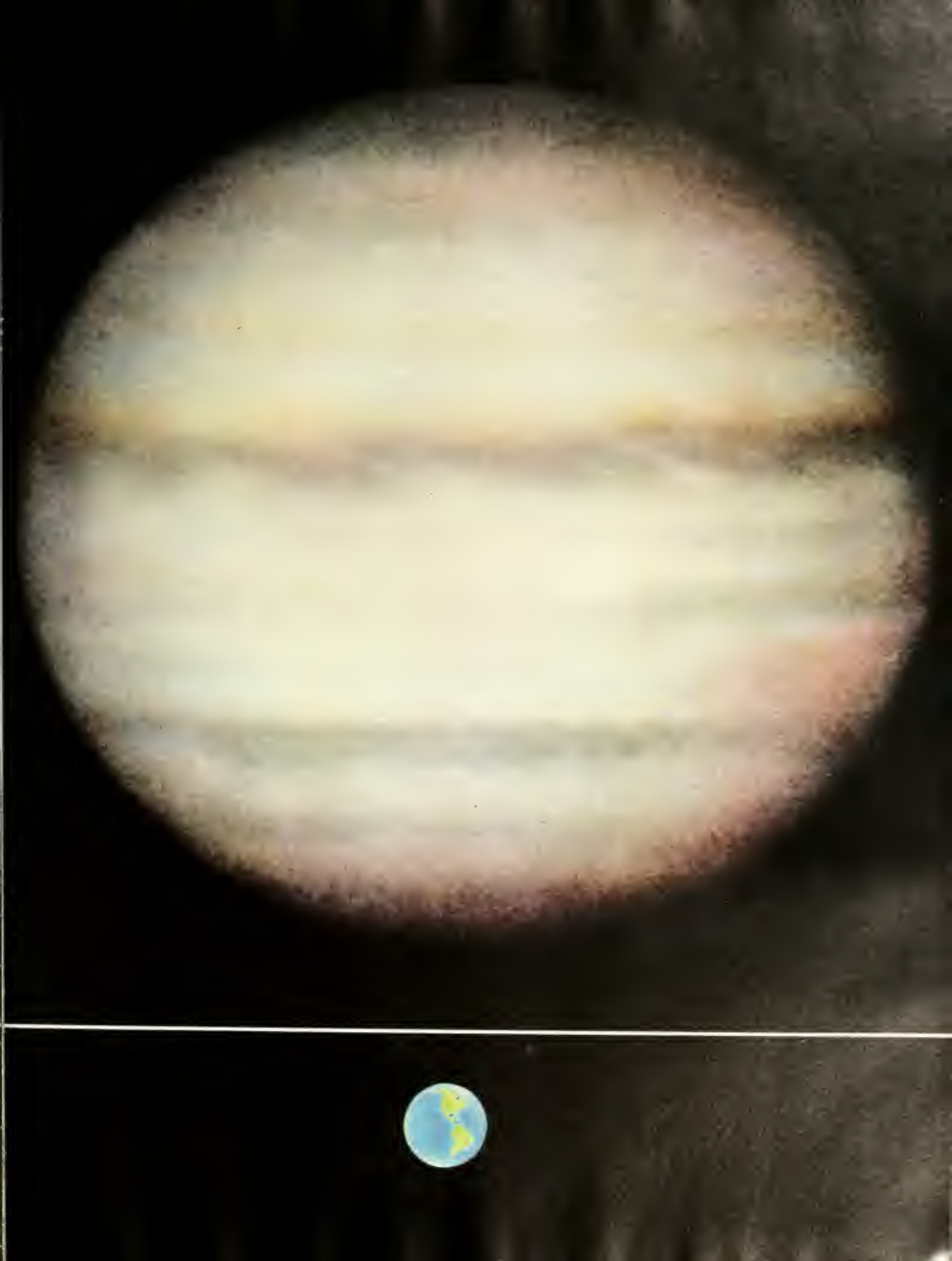
Stormy Jupiter

Four hundred million miles from earth is a hulking giant of a planet, with a mass more than twice that of all the eight other planets lumped together. As it ponderously circles the sun once every 12 earth years, it drags along a dozen satellites. Its clouded atmosphere—which may harbor a violent realm of torrential ammonia rains and titanic blizzards—is striped by vast, shifting, multicolored bands. These bands are not this planet's only markings. It has one of the most mysterious blemishes on the face of any planet: the Great Red Spot that comes and goes unpredictably, and is as wide as the earth. What lies beneath this decorated atmosphere may never be seen, because the pressure it exerts would crumple an exploring spaceship like tinfoil. The best guess is that the interior is mostly hydrogen, forced into a liquid or solid state—or both—by the pressures of the gases above it.

This planet is Jupiter, which seems to act as no true planet should. There is some evidence that Jupiter loses by radiation more heat energy than it acquires from the sun, and therefore it may be producing energy of its own—an activity ordinarily more characteristic of a star than of a planet.

JUPITER AND EARTH

The belts of frosty clouds that top Jupiter's atmosphere show up orange and gray in this telescopic photograph in contrast with the marking at lower right, the Great Red Spot. This puzzling blot ranges in coloration from brick red to dull gray. The sun's biggest planet, Jupiter is matched here to a scale representation of the earth, whose diameter is less than one eleventh of Jupiter's



MOONS IN ALL DIRECTIONS

Jupiter's satellites trace a varied pattern of orbits The four inner moons *(red)* provide a centerpiece of almost circular orbits, the farthest about a million miles out; a fifth inner satellite circles too close to Jupiter to be shown. Three other satellites *(purple)* orbiting about seven million miles out also have fairly circular paths But the four outer satellites *(brown)* travel elongated paths in the "retrograde," or opposite, direction from the other eight, furthermore, two of these outer satellites have "open" orbits that are never repeated from one circuit to the next.

A Swarm of Satellites

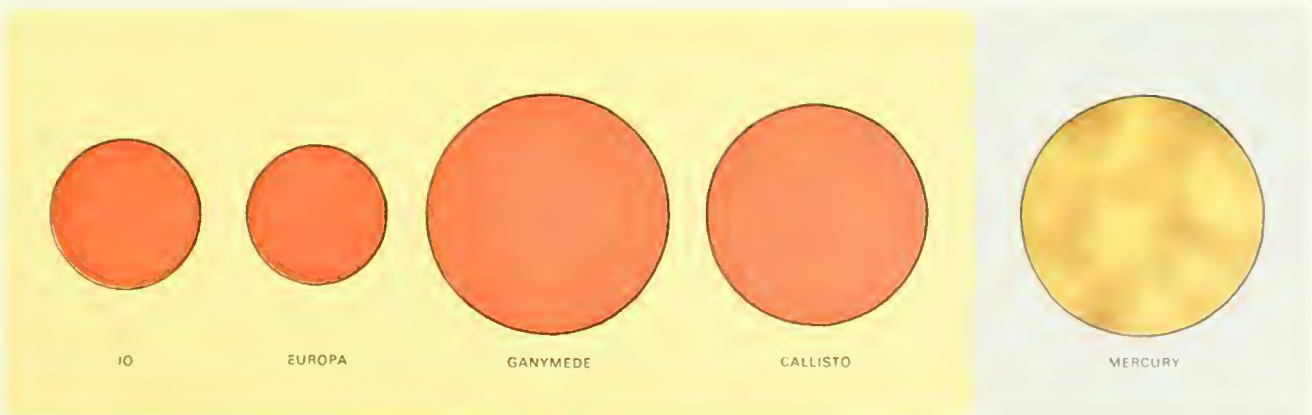
Jupiter's 12 satellites (three more than its nearest rival, Saturn) are every bit as remarkable as their parent planet. While most of them move in nearly perfect circles around the planet, a few make very elongated orbits. The inner eight orbit in the same direction in which the planet rotates, but the other four travel in the opposite direction from the others. These outer satellites are tiny, their average diameter probably less than 10 miles. They are so distant from Jupiter—about 14 million miles—that their behavior is markedly affected by the sun's gravitational pull, which makes their orbits uncertain. Some scientists think they are really just asteroids forced out of their former orbits between Mars and Jupiter by a gravitational tug-of-war won by Jupiter over the sun. Because they are small the outer satellites are very difficult to see. The last-discovered of these, which shines no brighter than the light of a candle seen from 3,000 miles away, was found only in 1951.

Jupiter's biggest, brightest moons are called Galilean satellites, after their discoverer. In size they loom over the outer satellites like beach balls over grains of sand.

The innermost satellite, known as V, is only 112,000 miles from Jupiter (about half the distance from the earth to its moon) and is about 70 miles in diameter. Jupiter's gravitational force causes tiny V to hurtle through space at 1,000 miles a minute, 26 times faster than the earth's moon.

THE FOUR BRIGHTEST

The four Galilean satellites circle comparatively close to Jupiter although one Callisto *(right)*, is more than a million miles away. The other three orbit in paths from 262,000 miles to 665,000 miles out. All four reflect light better than the earth's moon and two may have surfaces partially covered with an icy mixture of ammonia, nitrogen, carbon dioxide and water.



PLANET-SIZED MOONS

The Galilean satellites are so enormous that one of them, Ganymede, is actually 90 miles greater in diameter than the smallest planet, Mercury, as is shown in these scale drawings. Ganymede's diameter is 3,120 miles, while Mercury's is 3,030 miles. Callisto is next largest, measuring 2,770 miles, followed by Io and Europa with diameters of 2,020 and 1,790 miles.

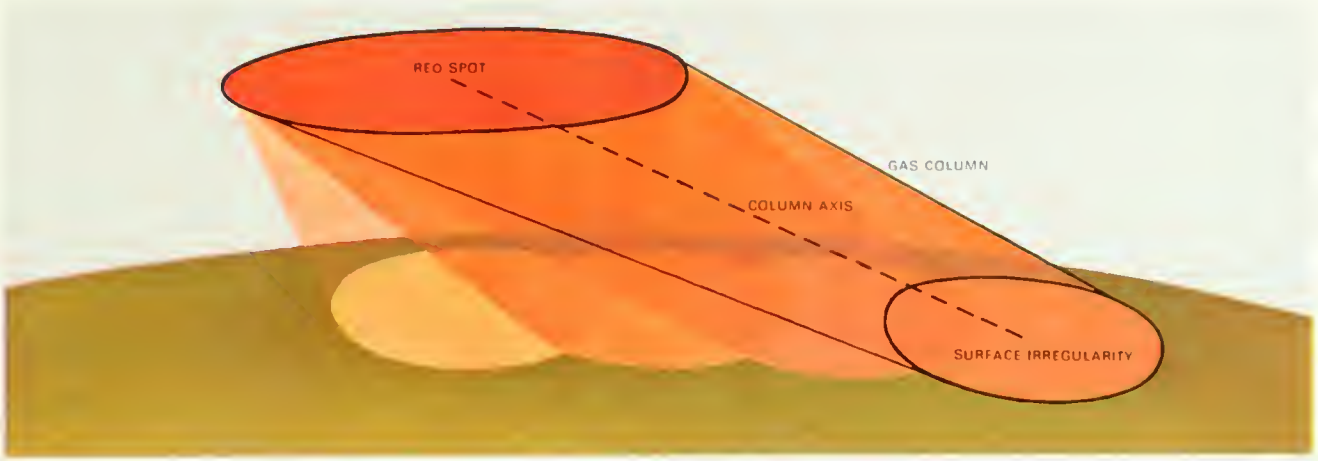
The Mysterious Great Red Spot

Jupiter's heavily clouded atmosphere is believed to be a raging mass of ammonia hail and earthlike snow. But riding tranquilly amid all this turbulence is one of the most unusual features in the solar system, the Great Red Spot. This is a giant oval marking, up to 30,000 miles long and 8,000 miles wide, that moves slowly in relation to its immediately surrounding clouds, but always remains in Jupiter's South Tropical Zone. It drifts within the zone, often changes color, and sometimes it disappears from view for years at a time.

Observed regularly since the late 19th Century, the Spot has been explained in many ways: as a result of volcanic emissions, as an island in the atmosphere, and even as another moon in the process of being formed.

The most widely accepted theory, illustrated here, has been advanced by Raymond Hide of the Massachusetts Institute of Technology. Hide believes that there must be a topographical irregularity on the surface of the planet, either an elevation or depression. The rapid rotation of Jupiter prevents the flow of moving gases over this irregularity, forcing them to pass around it. This creates a tall column of relatively stagnant gas that rises through the atmosphere. The top of this column is seen as the Spot. When the Spot seems to disappear it is really still there. But for some reason its color has changed to dull gray, which makes it blend with the outermost layer of clouds.

Jupiter's Great Red Spot appears at the top of a gauzelike column of gas in this illustration of Hide's theory. The gas column rises above



A WANDERING COLUMN

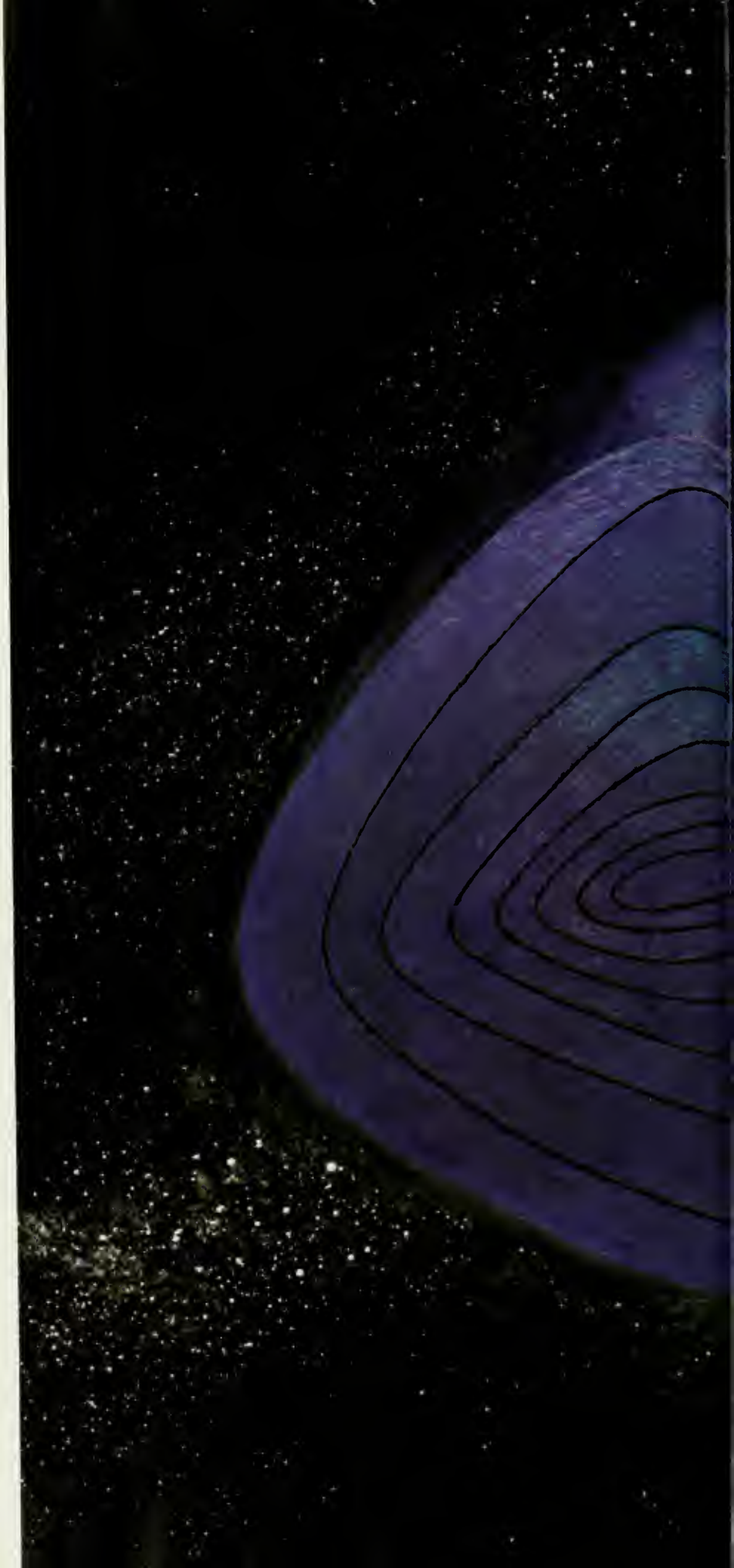
The location of the Spot in Jupiter's atmosphere does not necessarily pinpoint the surface irregularity that causes it. The irregularity could be directly underneath the Spot or it could be out to one side, depending upon how the column of gas is inclined in relation to the surface. When the column is slanted at an extreme angle, the line from the feature to Spot *(dotted line)* is parallel to the axis of Jupiter's rotation.

some sort of unusual feature on the planet's surface. The atmosphere's clouds, which are actually opaque, are rendered as transparent here

Outside Clues to What's Inside

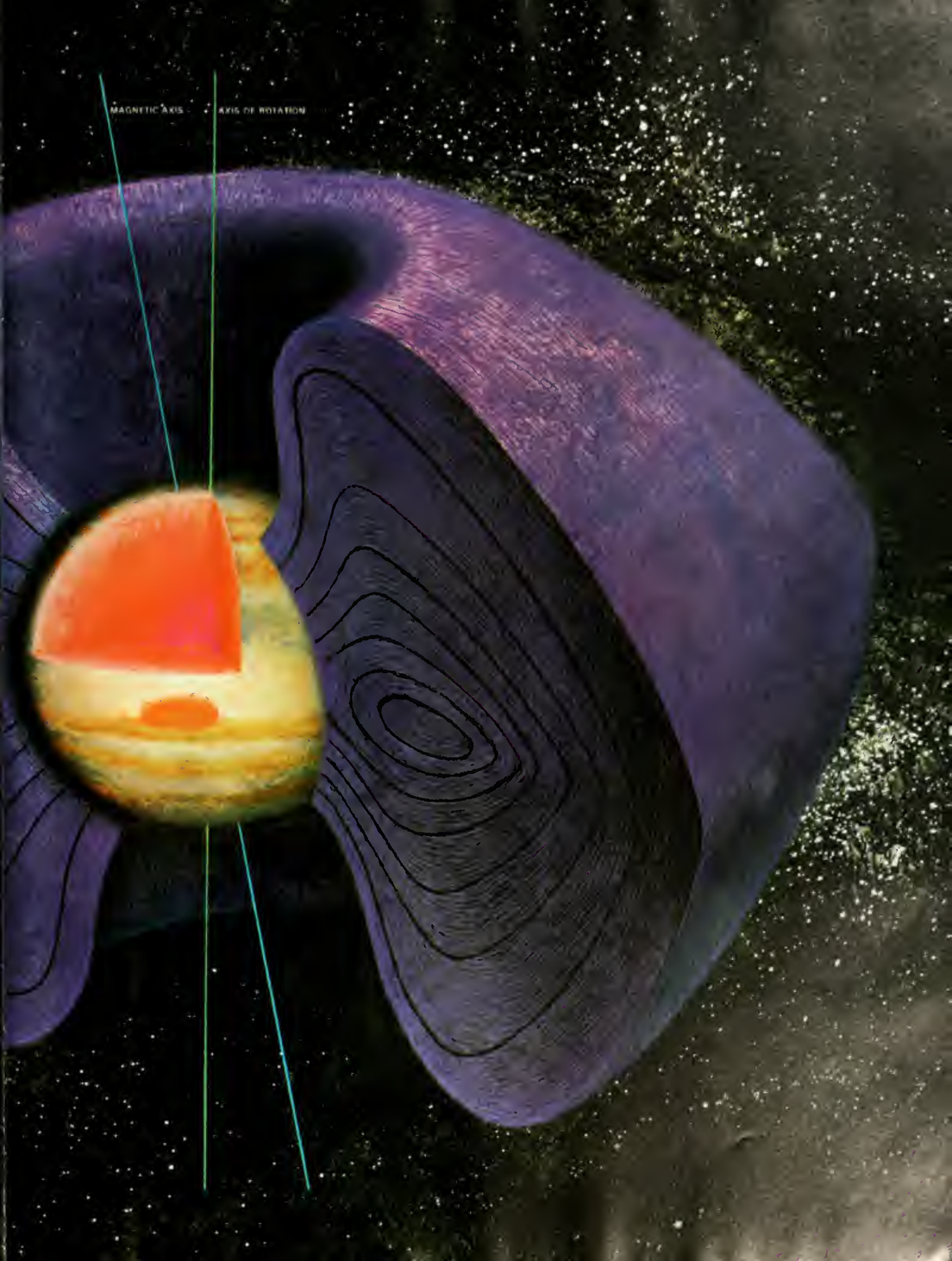
One of the most revealing recent discoveries about Jupiter is that, like the earth, it has a powerful magnetic field. This is indicated by a vast, doughnut-shaped belt of electrically charged particles that encircles the planet—a ring similar to the Van Allen belts of charged solar particles held prisoner by the earth's magnetic field. Only the earth and Jupiter are known to have these belts, and some astronomers now reason that Jupiter, like the earth, must have a metallic core which acts like an electric generator to create a magnetic field. Since Jupiter is composed largely of hydrogen, the core must be mainly a solid form of hydrogen compressed and heated into a metallic state.

But what lies between core and atmosphere? Some scientists believe that there is an actual surface—a wrapper of rocks and ices. But most agree that the transition from solid core to gaseous atmosphere is gradual and that there is no discernible boundary; the internal pressures imposed by the planet's great mass are so enormous that the hydrogen of the atmosphere eventually is squeezed into a frothy slush unlike anything ever seen in a natural state on earth.



THE PARTICLES AROUND JUPITER

The invisible belt of charged particles that embraces Jupiter is diagramed here in purple color. The planet itself has been sectioned to show that Jupiter's temperature rises going toward the center *(red)* and also that it may have no detectable solid surface inside its atmosphere. The magnetic axis, around which the belt has formed, angles away from the axis of rotation


MAGNETIC AXIS
AXIS OF ROTATION

8

The Solar System and Beyond

The comet Ikeya-Seki, after circling the sun, passes the earth and heads for home—billions of miles beyond Pluto—late in 1965.

MODERN ASTRONOMERS believe that the solar system is by no means unique; far beyond its boundaries are uncounted billions of other planetary systems. Almost any star in the sky may, like our own sun, have its entourage of planets, some of which are likely to support life, even intelligent life. These systems cannot be observed directly, and the best way to reason about them is to gather every possible shred of information about the solar system, which is at present the only example of a planetary system that can be studied in close detail.

The solar system still harbors many mysteries. Most of the information about it comes from the earth, the moon, Venus, Mars and Jupiter, which are relatively easy to observe. But now the techniques of modern astronomy are penetrating the secrets of the planets toward the extremes of the system—Mercury, Saturn, Uranus, Neptune and Pluto—and beyond them the far-ranging comets and the planets of alien stars.

Within the solar system the smallest and innermost planet, Mercury, is notoriously elusive. It is hardly bigger than the moon (3,030 miles in diameter versus 2,160 miles), but it is not very distant from the earth, sometimes coming as near as 48,337,000 miles, and it is fairly bright. What makes it so difficult to study is its closeness to the sun; the angle between them is always less than that between the two hands of a watch at 1 o'clock. During the day the sun's blazing light complicates observation of nearby Mercury, and at night the planet disappears from view almost as quickly as the sun does. Mercury can be seen alone only when it is low above the horizon, just before the sun rises or soon after it sets. Observation at such low angles is seldom satisfactory because of the great distance that the planet's light must travel through the earth's murky and turbulent lower atmosphere.

Laboring under these handicaps, the most skillful observers studied Mercury for decades, trying to make a map of its surface. Their progress was slow and uncertain. But eventually most of them reached something like a consensus. Nearly all agreed that the planet revealed only one hemisphere no matter from what direction it was observed. This must mean, they thought, that only one hemisphere was ever illuminated: the planet therefore must always keep the same side toward the sun, just as the moon keeps the same side toward the earth.

Important consequences flowed from this conclusion. If the same side of Mercury always faced the nearby sun, that side must get extremely hot. The dark side, on the other hand, must be the coldest place in the solar system. Hardly any heat would flow from the planet's interior, and no warming winds would blow from the sunlit side. Mercury was then believed to have no atmosphere. If it ever had one in the past, so went the reasoning, the gases would have escaped or migrated to the perpetually dark hemisphere, where they would have been condensed by the cold and deposited in a solid form as immobile as rock. Early observations of infrared light supported this picture of Mercury by setting the temperature of the sunlit side at 780° F. The dark side gave no infrared readings at all and was judged to be close to absolute zero, −450° F.

The dramatic hot-and-cold, sun-facing view of Mercury prevailed for many years and can still be found in fairly recent textbooks. It remained unshaken until astronomers estimated the temperature of Mercury's dark side from its radio waves and found it to be at "room temperature," roughly 70° F. This discovery posed a riddle. If the same side always faced away from the sun, as the visual observers insisted, a large movement of heat would be needed to keep the dark side so warm. A dense atmosphere would do this, of course, but new and careful observations showed that, although Mercury does have some atmosphere, its density cannot be more than about one thousandth of the earth's. To keep the dark side at room temperature, this thin gas would have to circulate at impossible speeds.

Measuring Mercury's rotation by radar

The riddle was finally solved by radar astronomy. In 1965 the great radio telescope at Arecibo, Puerto Rico, measured the rotation of Mercury by the Doppler shifts of wavelength in radar echoes from it. These measurements showed that the planet does not rotate at the proper speed to keep the same hemisphere always facing the sun. Instead of rotating once in 88 days, as would be required to keep up with its orbital motion, it rotates once in about 59 days. This means that Mercury's night is long but not eternal. Sunrise comes—to all sides of the planet—at intervals of about 170 earth days. The surface material and thin atmosphere do not have time to cool off completely before the fierce sunlight starts heating them again.

Even though Mercury does not suffer from eternal heat and eternal cold, as was long thought, it does not seem a hospitable place for life. If it ever had a life-initiating atmosphere of hydrogen and other reducing gases, the heat of the nearby sun probably drove it away in too short a time for life to appear. The thin present atmosphere is likely to be transient, made of gases that came out of the interior rather recently and are too heavy to escape quickly into space. When unmanned spacecraft are sent to examine Mercury, they will probably report meteorite craters like the moon's, but unless something more remarkable is discovered on it, the planet is likely to remain a small, unattractive and uninhabited world, visited seldom if ever by space-age man.

But if space-age man should travel in the other direction—out from the sun—his journey would be much more rewarding. Beyond Jupiter he would encounter the most beautiful of all the planets, Saturn, whose symmetrical rings give it a matchless grace. There is nothing like these rings anywhere else in the solar system and Saturn has, besides, another unique property—its low density. If the whole planet could be placed in water, it would float. Though Saturn looks as solid as any other planet, its density is about the same as that of maple wood.

This low density is not hard to explain. Like Jupiter, Saturn is made almost entirely of hydrogen and helium, with small amounts of other gases and a peppering of heavy elements. Its total mass, however, is

only about one third of Jupiter's and does not provide enough gravitation to compress the gases so tightly. Saturn's diameter therefore is not much less than Jupiter's (75,000 versus 88,800 miles) while its density is about half as great. It probably has a central body of solid hydrogen much smaller than Jupiter's, and because the pressure of its atmosphere is lower it remains gaseous to a greater depth than Jupiter does.

Since Saturn is so far from the sun, the top of its atmosphere is naturally colder than Jupiter's. Measurements of infrared light show that the temperature above the clouds is −270° F., compared to Jupiter's −190° F. The upper atmosphere contains less ammonia and more methane, probably because the extreme cold has caused more of the ammonia to freeze and form the dense clouds seen at lower levels.

In many other respects, however, Saturn does resemble Jupiter. Saturn rotates in about 10 hours, which is slightly slower than Jupiter. It has light and dark bands parallel to its equator, doubtless caused by wind movements. They are not as numerous or sharply defined as Jupiter's, and since they do not exhibit as many fast-changing details, they are believed to be less turbulent. Saturn has nothing like Jupiter's Great Red Spot, but conspicuous temporary markings are occasionally seen on its surface. In 1933, for instance, an enormous white spot many thousand miles in diameter appeared suddenly on the equator and spread into a white band.

Saturn's decorative rings

Saturn's rings are better understood than its interior or atmosphere. During the early years of telescopic astronomy there was much debate about whether the rings were solid or made of many separate bodies. The question was settled conclusively when the speeds of the inner and outer edges of the rings were measured. If the rings were solid, they would have rotated around Saturn like wheels and their outer edges would have moved faster than their inner edges. The opposite turned out to be true. The inner edge of the innermost ring is the fastest-moving, while the slowest is the outer edge of the outermost ring. Each section of each ring is rotating at exactly the same speed as a satellite would at that distance.

This discovery proved that the rings are made of bodies on independent orbits; it did not tell how big they are or what they are made of. But as Saturn moves on its 29-year orbit around the sun, the rings appear to change their angle slowly. The slanted disk turns to a knife-edge and for a short time disappears entirely. No trace of it can be seen with the biggest telescope, indicating that the rings are thin.

The more the rings are studied the less substantial they appear. They have no detectable gravitational effect on anything. The way they reflect sunlight indicates that they are made of very small separate particles that cast shadows on each other. Evidence for this is that the rings brighten suddenly by as much as 30 per cent when the earth is directly between Saturn and the sun. At this time the dark shadow of each par-

ticle is directly behind it and is therefore hidden from an observer on the earth, making the ring look brighter. (For the same reason the moon's surface, which is covered with small, shadow-casting irregularities, brightens suddenly at full moon.)

Careful study of sunlight reflected from the rings leads to the conclusion that they are made of particles no bigger than grains of sand but rough on the surface, as if covered with microscopic ice crystals. Some astronomers think that the rings are only a few inches thick and that the particles fill 0.5 per cent or less of the volume of the rings.

The origin of the frail but spectacular rings is not yet settled. Possibly the particles in the rings are the remains of matter that never formed a satellite because it was too close to Saturn's powerful gravitation.

For radio astronomers Saturn is a puzzle. It emits microwaves that betray its outer temperature, but no loud chorus of longer waves like Jupiter's. Its silence may mean that it lacks the radiation belt that is the source of most of Jupiter's radio waves. Perhaps it has no magnetism to collect charged particles from the sun and shape them into a radiation belt, the way Jupiter does. But this chain of reasoning is risky; Saturn may be not mute but muffled. The planet may have a strong magnetic field, but the rings may act as a barrier that keeps the magnetism from forming a radiation belt.

SIX SATURN SATELLITES are depicted on this 1686 medal, one of a series honoring accomplishments during the reign of France's Louis XIV. In this period the Italian astronomer Giovanni Domenico Cassini, first director of the Paris Observatory, discovered four Saturn satellites as well as a major gap in the planet's rings—called the Cassini Division

Planets beyond the reach of the eye

With Saturn the classical solar system comes to an end. Besides the sun, earth and moon, only five planets—Mercury, Venus, Mars, Jupiter and Saturn—were known to the ancients. Even after the invention of the telescope, nearly two centuries had to pass before the British astronomer Sir William Herschel, in 1781, accidentally found a small faint disk among the pointlike images of the stars. At first he thought it was a comet, but after a few months its orbit proved it to be a planet. Herschel named it Georgium Sidus (George's Star) after King George III, but later it was renamed Uranus after a pagan god, like the other planets.

Uranus did not behave quite as it should. Year after year its orbit deviated from what was considered its proper course, and astronomers began to suspect that another, yet-to-be-found planet was influencing its orbit. In 1842, John C. Adams, a young mathematics student at Cambridge University, attacked the difficult problem of calculating the position of the supposed planet. In September 1845 he timidly asked Sir George Biddle Airy, England's Astronomer Royal, and James Challis, director of the Cambridge Observatory, to take a look at the sky where he thought the unknown planet should be. Neither of the lordly astronomers considered Adams important enough to be taken seriously.

Meanwhile the French astronomer Urbain Jean Joseph Leverrier made the same calculations and came to almost exactly the same conclusions. Leverrier was a famous man and when he communicated his results in 1846 he got quick attention. On September 23 the German astronomer Johann Gottfried Galle found the planet where Leverrier

told him to look. It was named Neptune after another god. At the time Leverrier got all the honor for its discovery, but modern astronomers now give equal credit to Adams.

Both Uranus and Neptune are very hard to observe because of their great distances from the earth, Uranus being 1,782 million miles from the sun and Neptune 2,784 million miles. Uranus is somewhat larger (diameter about 30,000 miles), while Neptune (diameter about 28,000 miles) is slightly more dense and massive. Both rotate rapidly, Uranus in 10 hours, 49 minutes and Neptune in about 15 hours. Both are Jupiter-type planets, made almost entirely of light materials that are gases at ordinary earthly temperatures.

Spectroscopy shows that Uranus has a large amount of methane, but all of its ammonia has presumably been frozen out of the atmosphere by its low cloud temperatures, about 300° F. It shows faint wind bands and therefore is probably covered with ammonia clouds in slow circulation. Neptune, whose cloud temperature is perhaps 20 degrees colder, has methane but no detectable ammonia. No wind bands have been reported on it, but some observers claim to have seen vague and uncertain blotchy markings.

Whether life is possible on the four big outer planets depends on whether they have regions in their atmospheres where water exists as a liquid and where energy is available in some effective form. Jupiter probably has such a region; Saturn may have one. Uranus and Neptune are progressively less promising, but both probably have the chemical elements needed for life. Until more is known about these two distant planets it would be rash to state categorically that neither of them has any zone between its cold atmosphere and presumably hot interior where chemical reactions that result in life can take place.

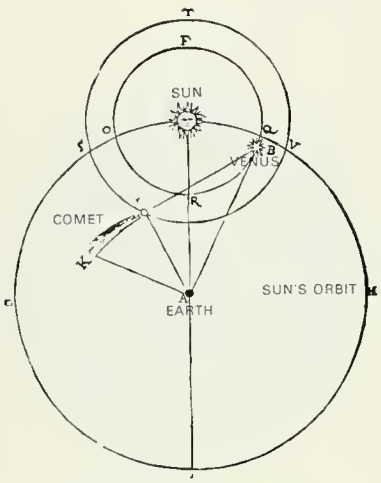
A PLANET PROPHET. French astronomer Urbain Jean Joseph Leverrier, commemorated in the medal above, correctly predicted the existence of Neptune in 1846 by calculations based on orbital irregularities of Uranus. But among the nine planets personified on the reverse of the medal *(below)* is Vulcan, which Leverrier positioned between Mercury and the sun. Computations based on modern physics indicate that Vulcan does not exist.

The great search for Pluto

The final member of the solar system was found in the same remarkable way as Neptune but with much greater difficulty. The American astronomer Percival Lowell, the proponent of the Martian canals, became convinced that even after the influence of Neptune had been accounted for the orbit of Uranus was still misbehaving. Neptune's orbit, which was less well known, showed similar disturbance. Both Lowell and Professor William H. Pickering of Harvard decided that the disturbing influence was an unknown "Planet X" and started to calculate its probable position. Lowell published his results in 1915, and his private observatory at Flagstaff, Arizona, searched the sky for the planet. Success did not come as quickly as it had for Leverrier. Not until 14 years after Lowell's death in 1916 did Clyde Tombaugh, an astronomer at Flagstaff, who used a specially designed telescope, find the elusive planet. It is so small and dim that it can hardly be distinguished from faint stars near it; but its slow motion on its 248-year orbit shows that it is a planet. It was named Pluto after still another pagan god, but the first two letters of its name are Percival Lowell's initials.

Not much is known about Pluto. Neither its mass nor density can be stated with certainty. Its diameter is about half that of the earth. Its elliptical orbit takes it from 2.79 billion to 4.65 billion miles from the sun. Small, cold and dark, Pluto is the planet least likely to support life.

The cold outer fringes beyond Pluto are the realm of the comets, those spectacular visitors that make quick dashes around the sun and disappear, seldom to be seen again. Their name comes from the Greek word meaning "long-haired," and refers to the luminous tails, like long hair blowing in the wind, that they develop when they approach the sun. During the ages of superstition they were feared as ill omens, and only recently has a good explanation been found for their behavior.



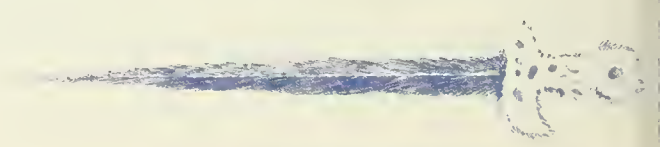
A COMET'S ORBIT was established by Danish astronomer Tycho Brahe with this diagram of the solar system published in 1577. In it he included four members of the system: the sun, the earth, Venus and a comet. Although he clung to the idea that the sun revolved around the earth, he broke with tradition by having Venus and the comet orbit the sun. The orbit he computed for the comet was incorrect, but he proved that comets were bona fide members of the solar system, shattering the prevalent notion that they were luminous atmospheric disturbances.

A cloud made of comets

Most astronomers now believe that a great thin cloud of comets surrounds the outermost planets, reaching out more than 10 trillion miles, almost halfway to the nearest stars. In this dark domain, where the sun looks no brighter than many another star, are more than 100 billion cometary nuclei. Most of them are a mile or so in diameter, though a few may reach diameters exceeding 50 miles. They are not necessarily spherical in shape. They may be irregular, and some astronomers believe they are composed of many small bodies traveling in company. While still resident in the cloud they do not look at all like comets. They are nonluminous and are made mostly of "ices"—that is, ordinary water ice mixed with solidified gases such as methane, carbon dioxide and ammonia. They are porous and their density is very low, probably about 10 per cent of water, or about that of balsa wood. Their surfaces may be covered with feathery structures like new-fallen snowflakes, but the ices inside are mixed with specks of dust that make them look like dirty packed snow. The general character of these curious objects has been learned by patient observation, but how or where they were formed is not certain. They may be small examples of the same condensation that formed all the planets out of gas and dust.

Most of the billions of comets stay in their great cloud, moving slowly on enormous orbits around the far-distant sun, but at long intervals some of them are disturbed by the gravitation of a passing star. A few of these move into interstellar space and are lost to the solar system. Others veer toward the sun, eventually to become the brilliant, long-tailed comets that are seen from the earth.

At first the comets move very slowly; the sun is so far away that they hardly feel its pull. But every hour, day and year they move a little faster, and the sun ahead grows brighter. After a comet has come close enough to cross the orbits of the outermost planets, its surface is warmed by the strengthening sunlight, and some of its more volatile



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material begins to turn to gas. A few of its icy "feathers" break off and follow the nucleus on its orbit in a rapidly growing cloud.

By the time a good-sized comet has crossed the orbit of Jupiter, the cloud surrounding its nucleus—called a head, or coma—is big enough to be seen with a telescope. As it plunges still nearer the sun, more gas evaporates, taking some of the dust along into space. The head swells enormously, sometimes exceeding 100,000 miles in diameter, and a brilliant tail begins to extend in the direction away from the sun. It is made of dust and gas driven out of the head by the pressure of sunlight and the "wind" of charged particles shot out of the sun. Sometimes the tail of a large comet is 50 million miles long, and the whole comet shines more brightly than anything in the sky except the sun and moon.

Around the sun at a million miles an hour

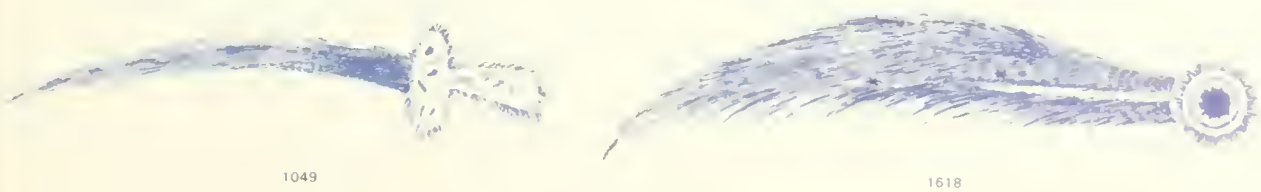
The evaporating gases leave behind a good part of the comet's dust as a layer that partially protects the underlying ices from the sun's heat, and this insulation helps them survive their encounters with the sun. If they pass very close, they whip around it with enormous speed, more than one million miles per hour, and shoot off into space with their tails pointing ahead, carried away from the sun by its light and particles.

Most comets depart on long, elliptical orbits that take them trillions of miles into space and keep them safe in outer darkness for thousands of years, but a few do not escape from the sun so easily. If they happen to pass near a large planet, particularly Jupiter, its gravitation may shunt them into short-period orbits around the sun. They then return repeatedly, each time losing a portion of their substance. When all their ices are gone, they disintegrate, leaving a stream of small particles that gradually spreads out thinly and loses its identity.

Every year the earth passes through several of these skeleton comets whose specks of dust shine briefly as shooting stars in the night sky. These cometary meteors, which are sometimes fairly bright, never hit the earth's surface, probably because they are made of fragile material that disintegrates quickly in the atmosphere. (The very bright fireballs that survive their passage through the atmosphere and hit the surface of the earth or come near it have nothing to do with comets, but are wandering chunks of metal or rocky material from the asteroid belt.)

The great cloud of the comets is the most distant province of the solar system. Beyond it lie the stars, at least 100 billion of them in the sun's own galaxy, the Milky Way. The question of whether they have planets has long been asked. The answer, which is now being given with increasing confidence, is yes. Astronomers now believe that all the stars were formed in the same way, by condensing out of gas, or gas and dust, and that planets are normal by-products of this process. Since the sun is an

THREE BRILLIANT COMETS terrified early observers, who considered them to be omens of disaster and described them as shown in these 17th Century illustrations a sword a saber and a feather. Despite Tycho Brahe s 1577 definition of comets as bodies which orbited the sun like planets *(opposite)*, the notion long persisted that comets presaged war or pestilence disasters which occurred regularly enough to lend substance to the belief



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ordinary star, there is nothing special about it and its planetary system. Other stars can have planets too, and positive evidence is accumulating that many of them do.

Why some stars wobble

No telescope can directly detect a planet revolving around a star; even the nearest stars are too far away. But planets can be detected by indirect methods. The most successful technique so far requires many accurate pictures which can be compared to reveal the star's motion. All nearby stars show "proper motion"—that is, motion of their own, not apparent motion that is due to any effect of the earth's movements on observations. If a star's proper motion wobbles slightly, the star must have with it at least one companion that cannot be seen. The wobble appears because the star and its unseen companion are actually revolving around a common center, like partners in a waltz, but only the large star can be seen. If the mass of the large star is known, as is sometimes the case, the mass and orbit of the companion can be calculated.

This method of detecting the companions of stars by the wobble they cause can be used only on stars that are the sun's closest neighbors, and it has not detected objects smaller than Jupiter. Its success, nevertheless, has been extraordinary. Barnard's star, the nearest single star to the sun, turns out to have an invisible, or dark companion with only 1.5 times the mass of Jupiter. This is the smallest planet discovered beyond the solar system thus far, but three out of the 12 stars nearest the sun are already known to have some sort of dark companion. It is safe to assume that if a star has one planet it very likely has others formed by the same process, and that stars too distant to be examined for planets are likely to have them too. In fact, it appears that planetary systems are common possessions of stars. It is probable that the Milky Way galaxy with its 100 billion stars has several hundred billion planets, and there may be comparable numbers in other galaxies.

How many of these innumerable planets may have life? The answer to this fascinating question depends on a large number of unknown factors. Planets that are similar to the earth in mass, surface temperature, atmosphere and history are probably relatively rare, but this strict set of conditions may not be necessary. If it turns out that life can exist on Marslike or Jupiterlike planets, the number of favorable habitats will be enormously increased. It is also possible that life can appear on planets that do not resemble any examples in the solar system. But even if strict conditions are necessary, the statistics are strongly in favor of life.

A great deal of thought, some of it intelligent, has been invested in speculation about the creatures that may inhabit planets or other environments throughout the universe. One school of thought believes that life requires conditions narrowly similar to those on earth and will develop—if it develops at all—along similar lines. Advocates of this doctrine of convergence point out that cold-blooded, water-breathing tuna and warm-blooded, air-breathing porpoises are only distantly related,

but they have closely similar forms because they both need excellent streamlining to move through the water rapidly. Therefore, in this view, large land animals that evolve on an alien planet somewhat like the earth are apt to have four limbs and a head containing their mouth and principal sense organs, because this is the most effective pattern.

The whole convergence idea is challenged by the broader view that life can develop under widely different conditions and take widely different forms. It is possible to imagine any number of novel environments and design living organisms to fit them, but no one should flatter himself that he can do it correctly. According to this doctrine of divergence, the outcome of evolution is largely a matter of chance, even though living conditions in various places may be closely similar.

The earth's modern organisms have some four billion years of history behind them, during which evolution explored innumerable blind alleys. Every large, advanced creature is the product of literally billions of mutations, most of them imperceptible, which had the effect of giving the creature's ancestors, age after age, a survival advantage over their competitors. Under slightly different conditions, or as the result of mere accidents, a different form might have won the battle for continuance. Many evolutionists believe that if the primitive earth were to evolve life all over again, there would be no appreciable chance that an animal physically resembling man, or even any of the mammals, would evolve.

Intelligent life on other planets

The question of whether alien planets have intelligent beings on them is a still-more tangled one. It is by no means certain that intelligence of human quality is the normal culmination of evolution. Some conditions may be favorable to life but not to high intelligence. The earth's oceans, for instance, have no appreciably intelligent creatures, except for mammals such as porpoises and seals that have returned to the water. To judge by this analogy, which is risky, an alien planet that is completely covered by water will probably have no animals more intelligent than the earth's fish. The human combination of large brain and tool-holding hand is even more fortuitous. A long series of special circumstances was necessary to develop it. If any of them had been lacking, the earth might have continued for billions of years more, perhaps for the life of the solar system, without achieving really high intelligence.

On the other hand, intelligence undoubtedly has important survival value. Evolution on the earth has generally moved in the direction of more highly developed brains. Fish have better brains than the marine worms from which they evolved, and amphibians, reptiles and mammals have successively better ones. If man had not developed his large brain, some other mammal, perhaps the raccoon, might have done so in a few tens of millions of years. Evolutionists point out that man's ancestor 70 million years ago is believed to have been something like the tiny, fierce tree shrew. Raccoons seem much more promising. According to this school of thought, intelligence is in the cards for any planet where con-

ditions are reasonably favorable for it.

But does intelligence imply that civilization exists? Here is another question hedged with unknowns. In the case of the earth, more than 200,000 years passed between the appearance of the first men with really large brains and the first human societies that can be called civilized. But with only one example to judge by, this incubation period cannot be called standard for all inhabited planets. It may be unusually short or long. In many cases, there should be plenty of time. The earth produced creatures capable of technical civilization in about five billion years, less than half of the 13 billion years that the sun is expected to shine steadily. Since smaller stars of the sun's type are extremely numerous and shine even longer, their planetary systems will have an even better chance—so far as time is concerned—to develop civilizations.

Even when civilization has begun, a high technical civilization is by no means certain. The first civilized human communities were agricultural villages in the Middle East about 10,000 years ago. Since that time human civilization has experienced many ups and downs. There was a major decline after the early flourishing of the ancient empires in Egypt and Mesopotamia and a parallel dark age after the fall of the Roman Empire. Other cultural centers, such as China, also had dark ages. For many long periods it must have seemed that civilization was a self-limiting process that could never rise above the handicraft level.

Civilizations in outer space

At present human culture is in an unprecedented state of rapid development. For the first time it has become technical and scientific and has found ways to unlock an apparently limitless storehouse of new powers. Its progress grows faster and faster; all its curves soar upward, and the limit is nowhere in sight. It is tempting to assume that civilizations on other planets normally reach the same takeoff point and become as progressive and powerful as the earth's. Another step is to expect that if they are a thousand or a million years older, they must be vastly more advanced than the earth's civilization.

Neither of these assumptions can be justified by studying the single example of advanced civilization that we possess—that is, our own. Alien civilizations may not develop in the same way as the earth's. They may exhaust totally the ready resources of their planet and return to a more primitive condition. Their individuals and societies may be repelled by change and make sure that it does not take place. They may destroy themselves with all-too-effective weapons.

It can be argued, however, that high civilization has survival value and will therefore be favored by cultural evolution. A civilized group will generally prove stronger than a primitive one, and a high technical civilization will overcome a culture that clings to pretechnical ways. This has happened so often on the earth that it seems to be a law of nature. It is happening now and therefore, say the optimists, it is safe to assume that some of the planets that have developed intelligent life

far in the past will have achieved technical civilization and soared far beyond the earth in knowledge and power.

If wonderful civilizations exist among the stars, it is only natural that human beings would want to visit them, or at least to communicate with them. Both these enterprises are fantastically difficult. Even the nearest stars are so enormously far away that to reach them not only must space be overcome, but also time. If a spaceship sets out for nearby Barnard's star, about six light-years away, at the steady speed of 100,000 miles per hour, the voyage will take 40,000 years, and before it is fairly begun the crew will die of old age. Travel at greater speed, even at a major fraction of the speed of light, will not help much, especially for journeys to more distant and more interesting stars.

A 200-year trip in 20 years

Besides the unattractive recourse of putting the crew in deep freeze for thousands of years, the only known way out of this impasse is to travel close to the speed of light itself, the ultimate speed limit of the universe. If this can be accomplished, an extraordinary thing will happen. As one of the strange consequences of relativity, time will slow down in the spaceship, and the men will reach their destination in what for them will be a few years. Suppose, for instance, that a spaceship sets out for a star 100 light-years away and accelerates steadily at the rate of a falling object on the earth. After the ship passes the midpoint of its journey, it decelerates at the same rate. During most of the trip it will be moving at close to the speed of light. For members of the crew, time will slow down, but they will feel no difference, and the round trip will take only 20 of their years. For the people they left behind on earth, time will not slow down. More than 200 years will have passed before the ship returns, and the great-grandchildren of the crew will be dead.

Even the most hopeful would-be travelers of interstellar space do not believe that such a relativistic journey will be possible in the immediate future. But they are confident that someday the trip will be made. They rely on the ever-increasing speed of human technical and scientific progress. Three hundred years ago no one on earth had even seen the crudest working steam engine. Now the earth has spacecraft that voyage to Mars. Three hundred years hence the men of the future may well have discovered some unsuspected way to travel to the stars.

Until that time approaches, the most promising way to make contact with high civilizations on alien planetary systems is to listen for radio messages from them. Though difficult, this is by no means impossible. Radio telescopes no bigger than those existing today on the earth could communicate with similar telescopes on planets tens of light-years away. Within that distance are thousands of stars, many of which are sure to have planets, and it is quite possible that radio messages from civilizations on some of them are reaching the earth now. The first sign that life exists among the stars may be radio signals that mark meaningful pulses on the recording tape of an earthly radio telescope.

OTHER SOLAR SYSTEMS that have been detected in our galaxy are listed below. Each consists of a nearby star and at least one planet which orbits it as the earth orbits the sun. None of these planets has ever been seen. But astronomers have deduced their presence and size by studying the motions of the stars closest to earth. Those moving in wavering paths are believed to be affected by the gravitational attraction of planets. Although the planets may be up to 20 times the mass of Jupiter, they are too small and reflect too little light to be seen from earth. The shaded area contains the names of stars whose companions, while strongly suspected, have not yet been confirmed. There may be many more bodies in each system, but only the largest can be detected with the present technique.

STAR	DISTANCE FROM EARTH (LIGHT YEARS)	MASS OF COMPANION RELATIVE TO JUPITER
BARNARD'S STAR	6.1	1.5
LALANDE 21185	7.9	10
61 CYGNI	11.1	8
BD + 5° 1668	12.4	20
CI 2354	15.1	20
BD + 20° 2465	15.5	20
BD + 43° 4305	15.7	20
CIN 2347	25.5	20

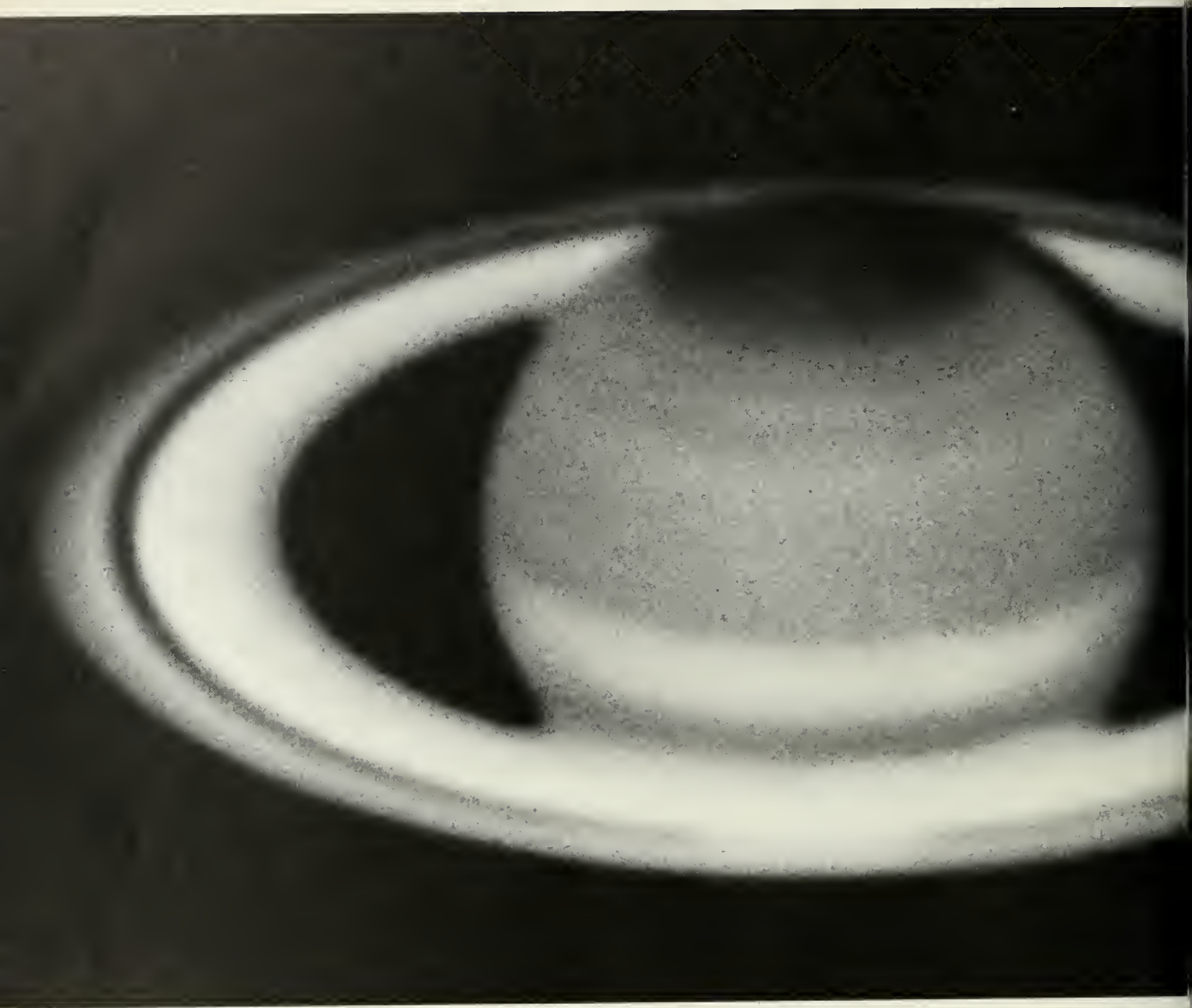
Life on Other Worlds

Man has always been fascinated by the possibility of life on other worlds. As long ago as the Second Century, science fiction writers were peopling the universe with bizarre creatures. When scientists began to develop instruments capable of analyzing distant planets, they generally dismissed the possibility of extraterrestrial life. The atmospheres and temperature ranges of those planets seemed too different from those of earth, which is still the only known life-supporting planet. In recent years, however, scientists have begun to change their minds. They understand how life might have originated under conditions that would appear alien to us now. At the dawn of life on earth, its atmosphere probably resembled that of such apparently hostile planets as Jupiter. Accepting the possibility of life is one thing. Proving it is another. Great interplanetary distance, suggested by the scale drawing at right, is still the major obstacle to exploration. But scientists are developing the machines and techniques for finding life, preparing for the inevitable day when those distances are spanned—and man makes his first contact with living beings on another world.

PLANETS ON AN EARTHLY SCALE

Interplanetary distance, the greatest obstacle to the discovery of life, is suggested in the map at right, drawn to the scale of 150 miles to 93 million miles—the distance from the sun to the earth. If the solar system were shrunk and placed on a map of Europe and Africa, the sun would be in Norway while Pluto, the farthest planet, would lie 6,500 miles south at the Cape of Good Hope.

EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
PLUTO

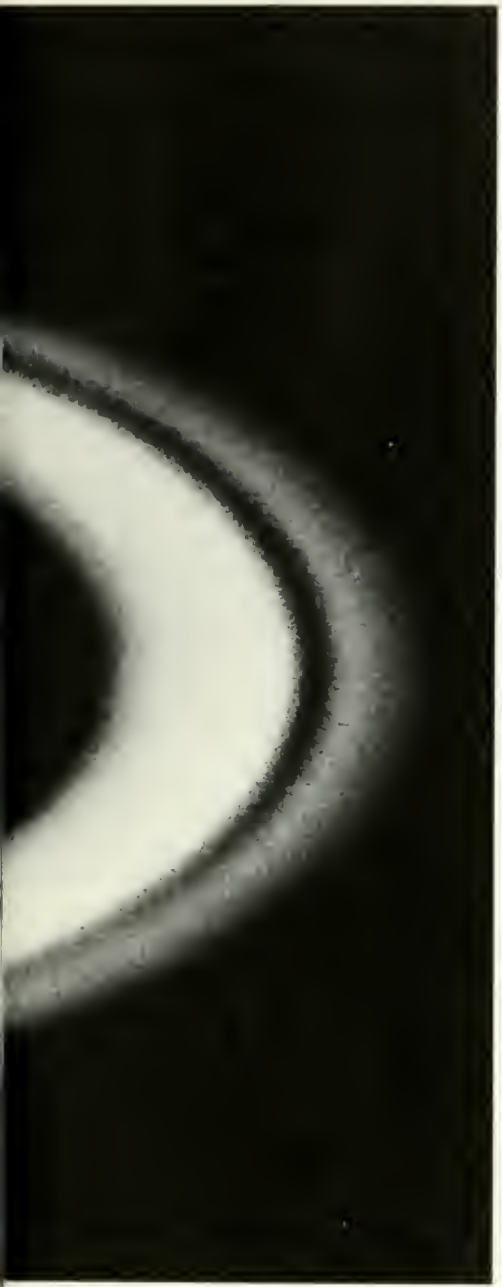


Far from the Warming Sun

Incapable of supporting any form of life: that was once the undisputed verdict on the four outermost planets—Saturn *(above)*, Neptune, Uranus and Pluto *(opposite)*. The evidence was their extremely low temperatures and their complete lack of oxygen.

But this verdict is now open to reasonable doubt. The fact that Saturn, Uranus and Neptune have atmospheres at all suggests the presence of life's precursors. Though Pluto probably has little or no atmosphere—and thus is much less likely to sustain life—recent discoveries have shown that the atmospheres of the other three are chemically suitable for reactions that may be sufficient to begin life.

Also these distant planets are definitely not, as was once believed, uniformly subject to temperatures of −270°F. and below. The wan heat of the sun combined with the internal warmth emitted by the planets have been permanently trapped beneath their atmospheric envelopes. Temperatures on some of these planets are now believed to be comparable to that of a heated room on earth.



THE RINGED BEHEMOTH
Like a baleful eye, Saturn spins inside its rings of ice crystals *(above)*. Although they have a diameter of 171,000 miles, more than twice that of Saturn itself, the rings are only a few inches thick. Saturn also has nine satellites, not seen in this closeup photograph. Titan, the largest of them, has an atmosphere, but like Pluto it seems to be too cold to sustain life.

ONE OF A PAIR
Given a starlike sparkle by distortion in the telescopic lens, Uranus *(above)* hovers in the midst of its five satellites. Uranus' heavy atmosphere traps enough heat to foster the development of life. Even more exciting are indications of molecules which have yet to be identified.

A BRIGHT RESEMBLANCE
Neptune, a near-twin of Uranus, is shown with Triton, the closer, and larger, of its two satellites. Half again as far from the sun as Uranus, it nevertheless may harbor life. For spectroscopic studies show that its atmosphere has sufficient hydrogen to produce organic molecules.

THE OUTERMOST WANDERER
Pluto is so far away that it was not identified as a planet until 1930. It is so cold that even if it has an atmosphere, the likelihood of life is extremely small. Even through powerful telescopes it looks like a dim star, but these photographs offer proof that it is indeed a planet. Taken a day apart, they show the movement of Pluto among apparently motionless stars.

A Universe Teeming with Life

Despite its 10-billion-mile diameter, the solar system, presided over by the sun *(below)*, is dwarfed by the Milky Way galaxy to which it belongs. But the Milky Way itself, containing 100 billion stars, is only a mote in the universe. There are billions of such galaxies, each with its own myriad stars, and most of these stars have their own planetary systems. If only 1/10,000 of 1 per cent of those planets harbors a technical civilization—and this seems to be a conservative estimate—the universe must teem with more than 100 trillion civilizations.

OUR STAR, THE SUN
Despite its importance to life on earth, the sun, 864,000 miles in diameter (shown here darkly spotted with huge regions of cooled gases), is only an average star in size, brilliance and age. It lies three fourths of the distance from the center to the edge of one of the galaxy's spiral arms.

A BRIGHT COMMUNITY OF SUNS
The Milky Way galaxy *(right)* is a flat, spiraling mass of stars. This view is toward the center, 30,000 light-years from earth; the entire galaxy is 80,000 light-years wide. The sun, revolving around the center at 480,000 mph, takes 250 million years to complete a single circuit.

M31, THE MILKY WAY'S TWIN
The great galaxy M31 in the constellation Andromeda, 2 2 million light-years away, is similar to the Milky Way in appearance, with its spiral arms swirling out of the bright, densely packed nucleus The two glowing disks above and below M31 are smaller satellite galaxies.

GALAXIES LIKE GRAINS OF SAND
A cluster of galaxies glitters at the outer range of the 200-inch telescope at Mount Palomar, California They are seen as they existed a billion years ago; they are so far away that their light, even at its speed of 186,000 miles per second, took that long to travel to the earth.

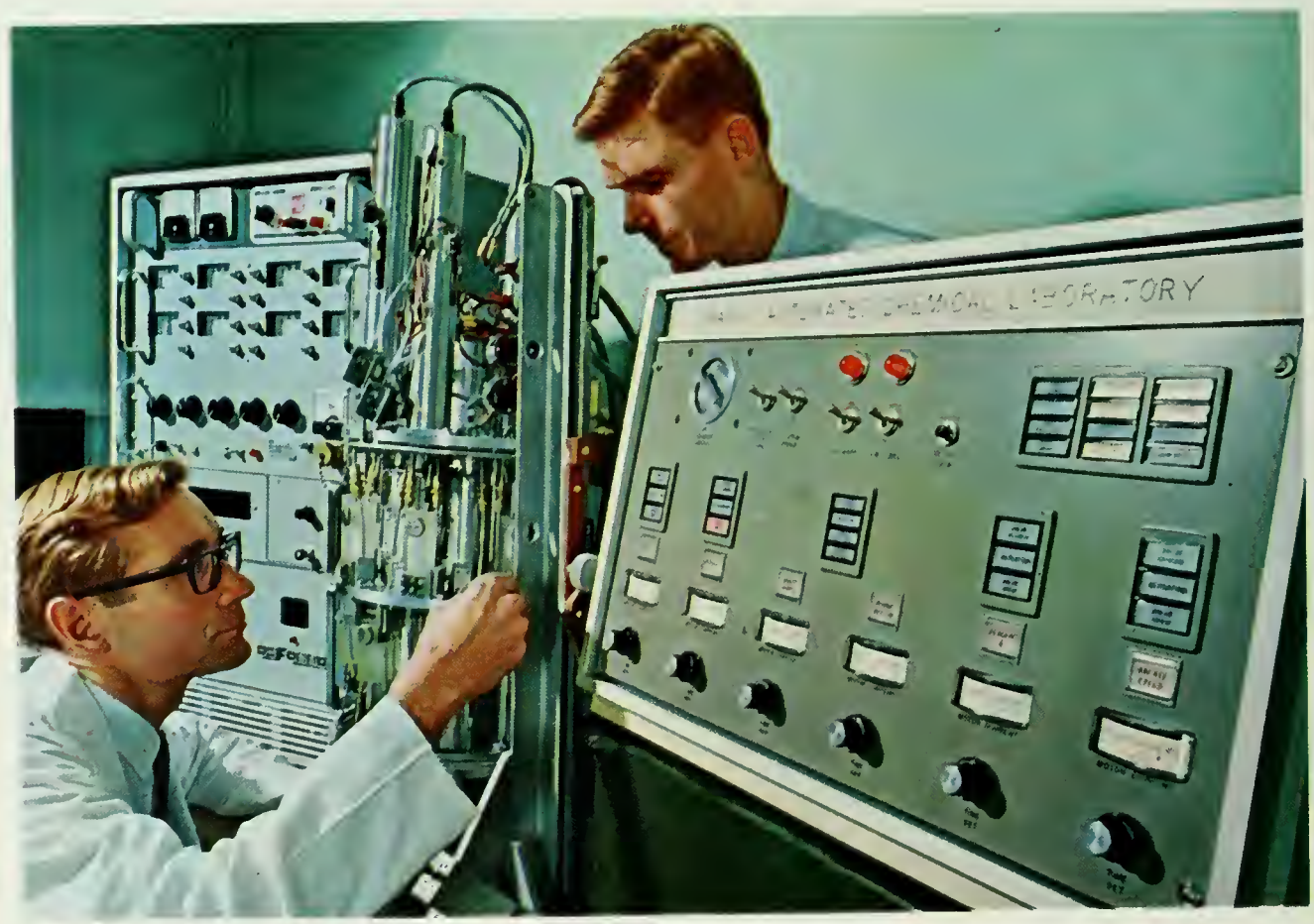
The Origin of Life

In the eons before life began, the atmosphere of earth consisted of methane, ammonia, hydrogen and water—a mixture that would kill most modern earthly life. But paradoxically—as scientists now know—these very gases were necessary for the beginnings of life. Prodded to react with each other by some form of energy—lightning or ultraviolet light—they formed the chemical compounds from which all life on earth has evolved.

To demonstrate this, scientists performed an experiment with the apparatus at right. Through a mixture of gases like those in earth's primordial atmosphere, they shot bolts of simulated lightning. The energy released caused a chemical reaction which yielded amino acids and other compounds found in all of known life.

Since there are other planets, such as Jupiter, whose atmospheres are very much like the young earth's, researchers tried another experiment. In the device at far right, they subjected the experimental atmosphere of methane and ammonia to the low temperatures of Jupiter. Even under such conditions, a spark produced organic compounds.

The results of both tests have encouraged space scientists to develop the portable laboratory below. Refined and adapted to an unmanned spacecraft, working models of such a laboratory will be sent out to distant planets. There they will search for the organic molecules that may be the beginning of the evolution of life.



AN EXTRATERRESTRIAL LAB

A miniaturized version of this automated chemical laboratory may one day radio back to earth the first reports of life-suggesting molecules. Carried to some distant planet by an unmanned space vehicle, the device will gather samples of soil by means of a scoop or suction mechanism. Then its test-tube assembly *(center)* will analyze the samples by means of ultraviolet light and light-sensitive photoelectric cells. The console panel at right supplies the prototype with computerized guidance; the panel at left provides the electric power for the laboratory.

A SPARK THAT MAY LEAD TO LIFE
A high-voltage electric spark arcs through a globe *(left)* containing a mixture of gases similar to those that comprised the earth's atmosphere more than four billion years ago. The resulting chemical reaction causes the formation of amino acids and other building blocks common to all life on the earth. Heavier than the gases, these compounds descend through the connecting tubes and are collected in the lower globe.

AN IMITATION OF JUPITER
Wreathed in streamers of evaporating liquid nitrogen, a Jupiter simulator at Ames Research Laboratories in Mountain View, California contains a mixture of methane and ammonia. Cooled by the nitrogen to −292° F., this atmosphere is roughly similar to Jupiter's. A spark creates hydrocarbons—compounds that are an early step in the development of life.

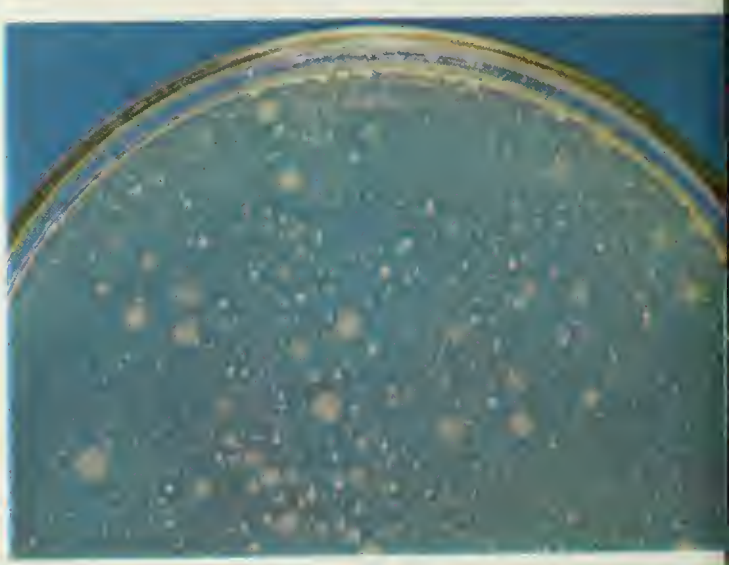
The Importance of Adaptation

MICROORGANISMS AND MARS
Despite the fact that they have been deprived of water and oxygen for several months, a group of molds gathered at random from soil and plants lead healthy lives in the laboratories of the Union Carbide Company in Tarrytown, New York. Their home for several months was the laboratory's Mars simulator, a small enclosure in which the atmosphere, temperature and length of day are similar to actual Martian conditions.

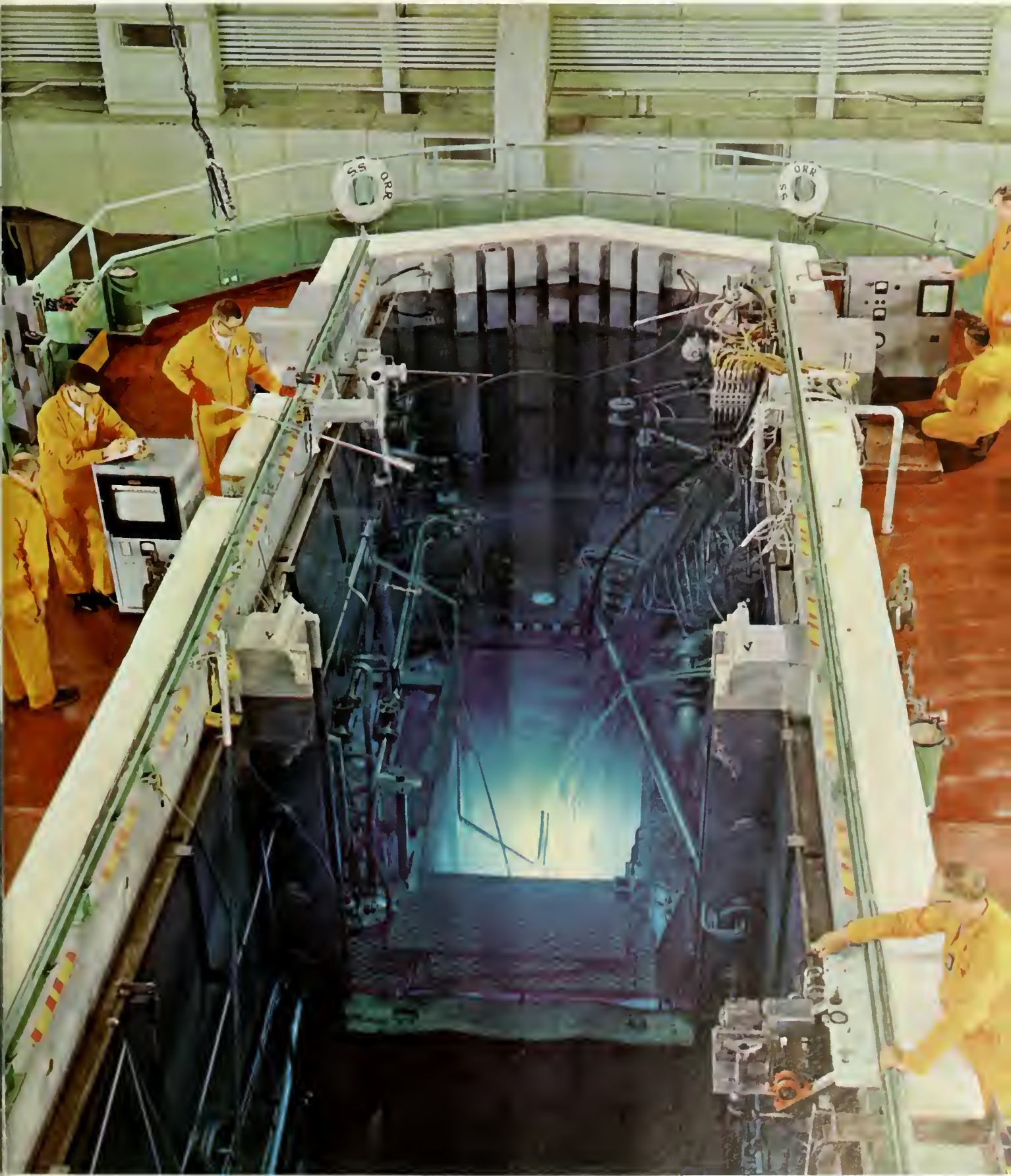
It seems impossible that any form of life could survive continued exposure to the intense radiation produced by a nuclear reactor *(opposite)*. Yet, one form of bacteria was found thriving within inches of the reactor's heart—its glowing atomic pile.

This is only one extreme example of the adaptability of life on earth. Penguins and lichens withstand the hostility of the Poles; lizards and cactus plants survive in the desert despite an almost total lack of water; fish live miles below the ocean's surface under pressures that would crush the toughest machine.

To exobiologists, who study the possibility of life on other worlds, the radiation-resistant bacteria were especially exciting, for they added yet another "intolerable" condition to the growing list of hostile environments in which, it is now known, life can survive. These scientists have already studied the effects on life of the hard conditions of other worlds. They have shown that earth-grown molds *(left)* and even some cactus plants can live in a Marslike atmosphere at low temperatures and virtually deprived of oxygen and water.



UNHARMED BY DEADLY RAYS
In the pink of health, pseudomonas bacteria *(above, left)* collected from the core of an atomic reactor survived radiation 1,000 times as strong as scientists had considered lethal to most bacteria. After being removed, the adaptable bacteria retained the ability to grow and multiply in a normal culture medium *(above, right)*. At one bacteria-infested reactor *(opposite)*, life rings facetiously initialed SS ORR (Oak Ridge Reactor) are actually of vital importance —unlike the bacteria, a man in the water could be hurt or killed by the intense radiation.


SS ORR
SS ORR

The Weird Forms Life May Take

Like jet engines with eyes, the imaginary creatures on these pages propel themselves by inhaling the atmosphere through their gaping mouths, expelling it in spurts rearward. The hydrogen it provides gives them shape and buoyancy. Like whales eating plankton, they take in organic material formed in the atmosphere and use the material as food.

These strange beings are one example of the alien forms scientists think extraterrestrial life may take. Literally gasbags, they could be the inhabitants of a Jupiterlike planet circling some distant star system.

These creatures would probably be no more typical of life throughout the universe than is man. Like dolphins, they could be intelligent. But lack of limbs, a necessity for building, would make them unsuited for a technical civilization. Their shape is especially adapted to their environment, a planet whose atmosphere is hydrogen, water, methane and ammonia. Such a planet—a ball of gaseous material that became progressively more dense from cloud tops to center—would offer its creatures no solid surfaces. They would live suspended like blimps in a cloudy world.

LIFE UNDER A DOUBLE SUN

On their planet, gasbags hover in the light of two stars, one (blue) hotter than its companion. Surrounded by an envelope of gases, such double stars are common, but not all boast a Jupiterlike planet. Such a world must orbit far from its double sun. It might otherwise circle only one of the pair or travel in a figure 8 between them, causing extreme changes in temperature.

The Solar System's Planets and Satellites

Like pieces of a puzzle, all the bits of data the astronomer gathers about the planets and their traveling companions the satellites serve to clarify his total view of the solar system. For example, by computing the mass of a planet and its diameter, he can estimate its gravity in terms of a man's weight and even draw some meaningful conclusions about the composition of its atmosphere. Armed with data about the planet's motion and atmosphere, he can then speculate intelligently on the possibility of life there. Similar deductions also reveal fascinating information about the 31 known satellites, which, while prisoners of the planets, often display quite different compositions and characteristics.

THE PLANETS

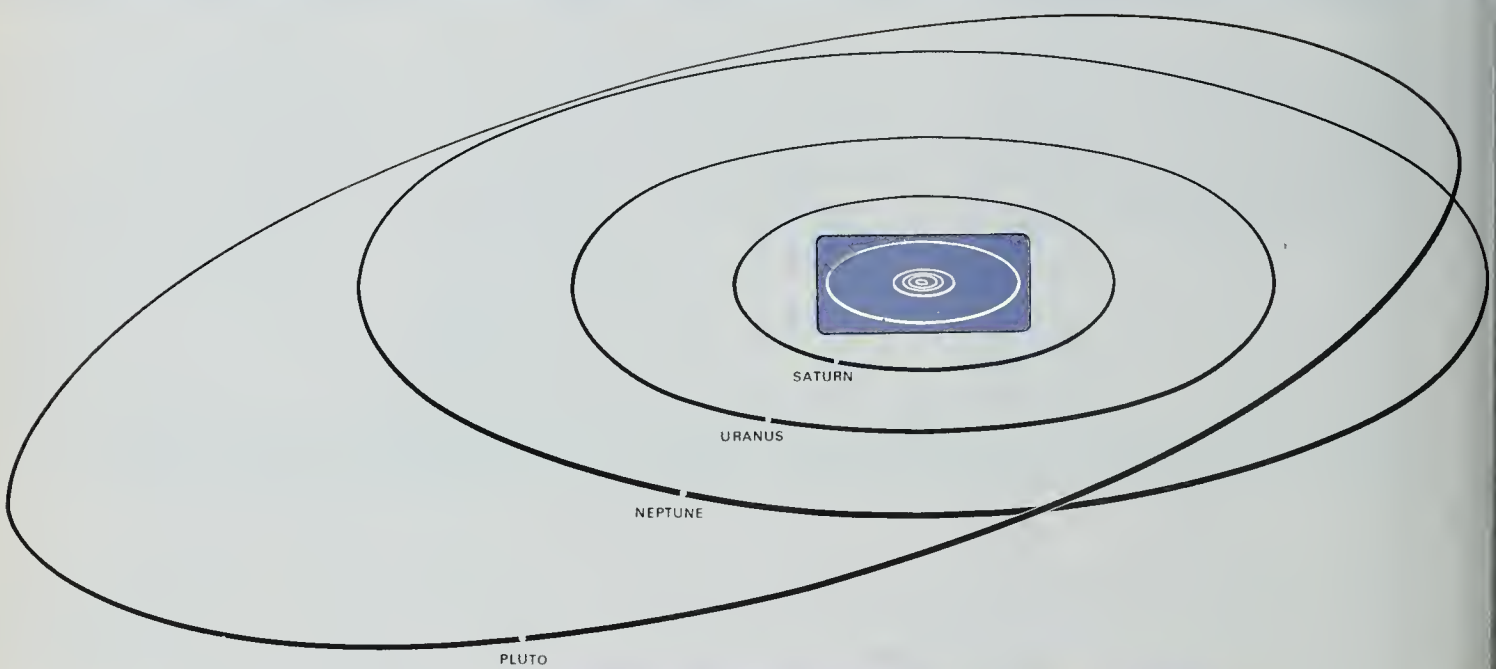
PLANET	AVERAGE DISTANCE FROM SUN (MILES)	ROTATION PERIOD (EARTH UNITS)	LENGTH OF YEAR (EARTH UNITS)	DIAMETER (MILES)	MASS RELATIVE TO EARTH	EQUIVALENT WEIGHT OF 150-LB PERSON	COMPOSITION OF ATMOSPHERE
Mercury	36,000,000	59 days (approx)	88 0 days	3,000	0 05	55	carbon dioxide
Venus	67,000,000	249 days (approx)	224 7 days	7,600	0 81	130	nitrogen? carbon dioxide, water
Earth	93,000,000	23 9 hours	365 3 days	7,900	1 00	150	nitrogen, oxygen, water carbon dioxide, argon
Mars	142,000,000	24 6 hours	687 0 days	4,200	0 11	55	carbon dioxide, nitrogen? water
Jupiter	486,000,000	9 8 hours	11 9 years	89,000	317 8	380	hydrogen, helium, methane, ammonia, water? neon?
Saturn	892,000,000	10 2 hours	29 5 years	75,000	95 2	160	same as Jupiter
Uranus	1,800,000,000	10 8 hours	84 0 years	30,000	14 5	155	hydrogen, helium, methane, ammonia? water? neon?
Neptune	2,800,000,000	15 hours	164 8 years	28,000	17.2	210	same as Uranus
Pluto	3,700,000,000	6.4 days	248 4 years	3,600	0 8 (approx)	unknown	unknown

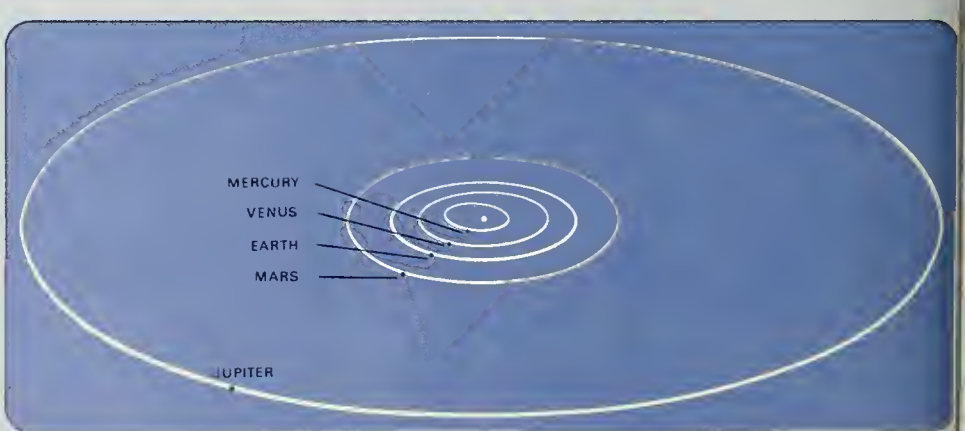
THE SATELLITES

PLANET	KNOWN SATELLITES (IN ORDER OF DISTANCE FROM PLANET)	YEAR AND PLACE OF DISCOVERY	DISCOVERER	AVERAGE DISTANCE FROM PLANET (MILES)	ORBITAL TIME (EARTH DAYS)	DIAMETER (MILES)
Mercury	none					
Venus	none					
Earth	Moon			240,000	27 3	2,200
Mars	Phobos	1877, U S	A Hall	5,800	0 3	5 (approx)
	Deimos	1877, U S	A Hall	15,000	1 3	3 (approx)
Jupiter	V	1892, U S	E Barnard	110,000	0 5	70 (approx)
	I (Io)	1610, Italy	Galileo	260,000	1 8	2,000
	II (Europa)	1610, Italy	Galileo	420,000	3 6	1,800
	III (Ganymede)	1610, Italy	Galileo	670,000	7 2	3,100
	IV (Callisto)	1610, Italy	Galileo	1,200,000	16 7	2,800
	VI	1904, U S	C. Perrine	7,100,000	251	50 (approx)
	VII	1905, U S	C Perrine	7,300,000	260	20 (approx)
	X	1938, U S	S Nicholson	7,400,000	264	10 (approx)
	XII	1951, U S	S Nicholson	13,000,000	631	10 (approx)
	XI	1938, U S	S Nicholson	14,000,000	692	10 (approx)
	VIII	1908, England	P Melotte	14,600,000	739	10 (approx)
	IX	1914, U S	S Nicholson	14,700,000	758	10 (approx)
Saturn	Janus	1966, France	A Dollfus	98,000	0 8	190 (approx)
	Mimas	1789, England	W Herschel	120,000	0 9	300 (approx)
	Enceladus	1789, England	W Herschel	150,000	1 4	400 (approx)
	Tethys	1684, France	D Cassini	180,000	1 9	630
	Dione	1684, France	D Cassini	240,000	2 7	550 (approx)
	Rhea	1672, France	D Cassini	330,000	4 5	950
	Titan	1655, The Netherlands	C Huygens	760,000	15 9	3,000
	Hyperion	1848, U S	W Bond	920,000	21 3	100 (approx)
	Iapetus	1671, France	D Cassini	2,200,000	79 3	500 (approx)
	Phoebe	1898, U S	W Pickering	8,100,000	550	100 (approx)
Uranus	Miranda	1948, U S	G Kuiper	77,000	1 4	200 (approx)
	Ariel	1851, England	W Lassell	120,000	2 5	500 (approx)
	Umbriel	1851, England	W Lassell	170,000	4 2	350 (approx)
	Titania	1787, England	W Herschel	270,000	8 7	600 (approx)
	Oberon	1787, England	W Herschel	360,000	13 5	500 (approx)
Neptune	Triton	1846, England	W Lassell	220,000	5 9	2,300
	Nereid	1949, U S	G Kuiper	3,500,000	359	200 (approx)
Pluto	none					

A Traffic Pattern for Planets

EARLY IN THE 17TH CENTURY, the great German astronomer Johannes Kepler published his three laws of planetary motion, describing the journey of the planets around the sun with amazing accuracy. Some of his conclusions, based on data left him by Tycho Brahe, were that planets travel in elliptical orbits, that they speed up when close to the sun, and that the inner planets orbit faster than those more distant. Mercury, for instance, travels at around 110,000 mph, while Pluto moves a tenth as fast. Kepler's laws apply to all planets in the solar system, although he knew of only six in his lifetime.





ORDERLY ORBITS
The planetary orbits within the solar system, all governed by Kepler's laws, are diagramed above and at right. Modern astronomers, using these laws and complementary physical laws formulated by Newton and Einstein, can now explain all planetary motion, even the eccentric orbit of Pluto. This planet crosses the orbit of neighboring Neptune, and some scientists believe that Pluto was once a satellite of Neptune.

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INDEX

Numerals in italics indicate a photograph or painting of the subject mentioned.

A

Absorption spectra, 63, *64, 65, 71*
Adams, John C., 172, 173
Adaptability of life, 116-117, 136-137, 188
Adenosine triphosphate, synthesis of, *39*, 40
Adonis, asteroid, *135*
Africa, drift of, 37, 58, *map* 59
Airy, Sir George Biddle, 172
Albedo, 89-90
Aldehydes, 39
Alfvén, Hannes, 30
Algae, 117
Almagest, of Ptolemy, 12, 13
Alphonsus crater, lunar feature, 89, *102-103*
Ames Research Laboratories, Mountain View, Calif., *187*
Amino acids, laboratory synthesis of, 39, 186, *187*
Ammonia, as atmospheric component, 43, 190; detection on planets, 68; in early earth atmosphere, 38, 39, 41, 186; in early Mars atmosphere, 136; in Jupiter's atmosphere, 153, 155, 159, 164; in Saturn's atmosphere, 171; in synthesis of organic molecules, 39, 159, 186, *187;* in Uranus' atmosphere, 173
Anaximander, universe of, *20*
Andromeda, constellation, 185
Animal life: evolution of, 41; possible extraterrestrial form, *190-191;* variety of, *54-55*
Antarctica, *50-51*
Antoniadi, Eugenios M., Mars maps of, *143, 147*
Aphelion, *25*
Apparent motion, 176
Arabs, contribution to astronomy, 12
Arctic, *52*
Arecibo, Puerto Rico, radio telescope, *74-75*, 170
Ariadaeus rill, lunar feature, *101*
Aries, constellation, 23
Aristarchus, 12, 13
Arrhenius, Svanté August, 124, 125
Asteroid belt, *135*, 144, 175
Asteroids, 37, 135, 163; impacts on moon, 85, 87
Astroblemes, *88, map* 89
Astrogeology Branch of U.S. Geological Survey, moon prohe projects, *104-107*
Astrology, 11, *141*
Astronauts, on moon, 83, 84, 92, *106*
Astronomy: early history of, 9-15, 16, *17, 20-25*, 61-62, *108;* modern instruments and techniques, 62-67, 68, *69-81. See also* Optical astronomy; Photographic astronomy; Radar; Radio astronomy; Radio telescopes; Spectroscopic analysis; Telescopes
Atlantic shores, and theory of continental drift, 37
Atmosphere of earth, 33-34, 38-43, 83; altitude of, *graph* 56; as barrier to telescopic observation, 64, 66-67, 79; composition of early, 38-39, 186; composition, present, 41; effect of life on composition of, 39, 41; greenhouse effect of, 42, *114;* heat exchange, 42; infrared window of, 65, *diagram* 66; layers of, 42-43, *graph* 56, 57; mass of, 38; origin of, 38; radiation absorption by, *diagram* 38, 42-43, 57, 65, 67, 79, 85; radio window of, 65, *diagram* 66-67; reducing, 38-39, 41, 153; tint of, *32*, 33, 48; uniqueness of, 41; visible (optical) window of, 64-65, *diagram* 66
Atmospheres of other planets: greenhouse effect of, 112, 114; Jupiter, 153, 154-156, 159, 160, *161, 164-165*, 166; life zones in, 159, 173, 182, 183, *190-191;* Mars, 80, 131, 132, 133-134, 135-136; Mercury, 170; methods of study of, 63-*64, 65*, 73, 74, *78-79*, 80; Neptune, 173, 182, 183; Pluto, 182; reducing, 136, 153; Saturn, 171, 182; Uranus, 173, 182, 183; Venus, 78, 109-112, 114, *115*, 116, 125, 126-127, 128
Atmospheric turbulence, 64, 67, 79
ATP, synthesis of, *39*, 40
Auroras, 57, 158
Australia, tracking stations in, 77

B

Babylonia, 18; astrology, 11; tablet, *108*
Bacteria: fossil, *41;* pseudonomas, *188*
Bad seeing, 64, 67
Balloons, use for astronomical observation, 67, 68, 78-79, 112
Barnard, Edward E., 142
Barnard's star, 176, *table* 179; distance of, and travel to, 179
Basalt, 36, *57*
Batson, Ray, *105*
BD+5° 1668, planetary system, *table* 179
BD+20° 2465, planetary system, *table* 179
BD+43° 4305, planetary system, *table* 179
Bell Telephone Laboratories, 65
Big Dipper, 61
Bolometer, germanium, *72*, 73
Brahe. *See* Tycho Brahe
Brazilian rain forest, *52-53*
Bright-line spectrum, 63
Brightness, visual albedo, 89-90
British Isles, view of, from space, *46-47*
Bruno, Giordano, 14

C

California, space view of, 48, *49*
California Institute of Technology, 66; Owens Valley observatory of, *75*
California peninsula, drift of, 37, 58, *map* 59
Callisto, Jovian satellite, *163*
Camera, lunar probe, 104, *105*
Canadian tundra, *52*
Canal controversy, Mars, 131-132, 140, *142-143, 145*
Canberra, Australia, tracking station, 77
Canyon Diablo crater, Ariz., 87, *88, map* 89
Cape Kennedy, space view of, *48*
Carbon cycle, 41
Carbon dioxide: in carbon cycle, 41; in earth atmosphere, 38, 39, 41, 42, 67, 79; and greenhouse effect, 42, 43, 112; in Martian atmosphere, 134, 136; in oceans, 41; in Venus' atmosphere, 110, 112, 125, 126-127, 128
Carolinas, space view of, *32*
Carrier beam, 77
Cassini, Giovanni Domenico, 172
Cassini Division of Saturn's rings, *172*
Catastrophic theory of formation of planets, 34-35
Challis, James, 172
China: ancient seismograph, *34;* observation of supernova (1054), 13
CI 2354, planetary system, *table* 179
CIN 2347, planetary system, *table* 179
Circular motion of heavenly bodies, old concept of, 12, 13-14, *15, 22-25*
Civilization: development on earth, 178; technical, 178-179; technical, extraterrestrial, 179, 184, 190
Cladonia rangiferina, 90
Climate, earth, *52-53*, 83
Coesite, in astroblemes, *88*
Columbus, Christopher, 50, 80
Cometary meteors, 175
Comets, 85, 174-175; composition of, 174; density of, 174; Ikeya-Seki, *168;* myths, *175;* number of, 174; orbits of, *174*, 175; origin of term, 174; sizes, 174, 175; speed near sun, 175; tails of, composition and length, 175; Tycho's study of, *174*, 175
Computers, use in planet probes, *76-77, 186*
Continental drift, theory of, 37, *58, maps* 59
Continental shelf, *57*
Continents, theories on formation of, 36-37, 58
Convection currents: in earth atmosphere, 42; in earth's interior, 36, 37, *58*
Convergence of evolution, doctrine of, 176-177
Copernican system, 13-14, *24-25*
Copernicus, Nicolaus, 13-14, 16, 24, 26, 62
Copernicus crater, lunar feature, 86, 87, *95, 98-99*
Core of earth. *See* Earth core
Core of planets, and magnetic field, 36, 115, 136, 157
Cosmic dust, 85
Cosmic rays, 85, 93
Counterearth of Philolaos, 20, *21*
Crab nebula, 13
Crater formation, 85, *86*, 87, *88, 98-100*
Craterlets, *97*
Crust of earth. *See* Earth crust
Cultural evolution, 178
Cumulus clouds, *48*
Currents, inside earth, 36, 37, *58*
Cyanides, 39

D

Dark-line spectrum, 63, *64, 65, 71*
Darwin, Charles, 14
Darwinian evolution, 14, 40. *See also* Evolution
Decameter waves, Jupiter, 158
Deep Space Instrumentation Facility, Goldstone, Calif., *76-77*
Deimos, Martian satellite, 139
Densities of planets, 11
Dish antennas, *69, 74-75*, 77
Distances: interplanetary, 180, *181;* nearest star, 9, 179; of planets, determining, 68; of planets, from earth and sun *(see individual planets)*
Divergence of evolution, doctrine, 177
Doppler shift, 113
Double stars, *190*
Dumping, radiation belt phenomenon, 158
Dust, interplanetary and cosmic, 80, 85
Dust-and-gas-cloud theory of formation of solar system, 35, 44, 175

E

Earth, 10, 13, *24*, 44; age of, 58; albedo, 89-90; climates, *52-53*, 83; cross section of, *56*, 57; density of, 153; diameter of, 34; early history of, 34-41, 58; early recognition of roundness of, *12;* elements on, rare vs. common, 38; erosive forces, 84, 85; escape velocity, 84; ice ages, 93; interior of, 34-36, 44, *56*, 57 *(see also* Earth core; Earth mantle); light of, 83, 89-90; magnetic field of, 36, 43, 57, 85; meteorites and meteorite craters, 35, 85, 87-*88, map* 89, 99, 104; and moon, 83, 84; orbit of, 14; rotation of, 24, 36; seasons of, 10-11, *52-53*, 133; size comparison, *11;* surface features of, 33-34, 36-37, 41-42, *50-53, 57-58, maps* 59, 85 *(see also* Earth crust; Oceans of earth); surface temperature, 41-42, *114;* tilt of axis of, 10, 52; views of, from space, *32*, 33, *45-49;* wind system, 155. *See also* Atmosphere of earth; Life on earth
Earth-centered theory of solar system, 16, *17*, 24; Greek and Ptolemaic, 12, 13, *20, 22-23;* of Tycho Brahe, 14, *15*
Earth core, 34, 36, 44, *56*, 57; composition of, 34, 35, 36, 44; diameter of, 34, 57; inner vs. outer, *35, 56*, 57; formation of, 35, 36; methods of study of, 34, *35*, 57; temperature of, 36, 56
Earth crust, 33-34, 41, *56-57;* changes in, 36-37, *58, maps* 59, 85; composition of, 36, *57;* faults in, 34, 48, *49*, 58; formation of, 36; highest and lowest extensions, *57;* maximum thickness, 33, 57; minimum thickness, 57
Earth mantle, 36, *56*, 57; composition of, 36, 56; currents in, 37, *58;* lower vs. upper, *56-57;* methods of study of, 36, 57; thickness of, 36, 57
Earthquakes, 34; seismic waves, 34, *35*, 57
East African lakes, and continental drift, 37
Egypt: ancient, concepts of universe, *10*, 18; view of, from space, *46*, 47
Electromagnetic radiation, 61; penetration of atmosphere by, 64-65, *diagram* 66-67; velocity, 61; wavelengths, 61, *diagram* 66-67
Electromagnetic spectrum, 61, *diagram* 66-67
Elements, chemical: rare vs. common, as earth components, 38; spectroscopic detection of, 63
Elliptical orbits, discovery of, 14, 24, *25*
Emission spectrum, 63, *64*
Enlil, Sumerian god, *19*
Enzymes, 137
Eratosthenes, 12
Eros, asteroid, *135*
Erosion, 84, 85, 99; dust, *103*
Escape velocities, earth vs. moon, 84
Endoxus, 12; universe of, *22*, 23
Europa, Jovian satellite, *163*
Everest, Mount, *57*
Evolution of life, 14, 39-41, 54, 116, 177; adaptability, 116-117, 136-137, 188; cultural, 178; of intelligence, 177-178
Exobiology, 188. *See also* Life, extraterrestrial
Exosphere, 43, *graph* 56, 57
Explorer satellites, 36
Eye, astronomic observation by, 61, 64, 147

F

"Fairy castles," 90-91
Faults, in earth crust, 34, 48, *49*, 58
First Men in the Moon, The, Wells, *90*, 92
Flagstaff, Arizona: Astrogeology Branch of U.S. Geological Survey at, *104-107;* Lowell's observatory at, 173
Florida, drift of, 58, *map* 59
Fontana, Francesco, drawings by: of Mars, *133;* of moon, *85*
Fossils, early life, *41*

G

Galaxies, *184-185;* number of, 184; planets in, 176, 184; radio telescope studies of, 75
Galilean satellites of Jupiter, *163*
Galileo Galilei, 14, *62*, 118; manuscript by, *152;* telescope of, *60;* telescopic observations of, 61-62, 71, *84;* quoted, 62
Galle, Johann Gottfried, 172
Gamma rays, 61, 66; velocity, 61; wavelength, 61, *diagram* 66
Ganymede, Jovian satellite, *163*
Gas-cloud theories of origin of solar system, 26, 30, 35, 44, 175; Hoyle-Alfvén hypothesis, *30-31;* Kant-Laplace hypothesis, *26-27*, 28
Geb, Egyptian god, *10*
Gemini V photographs, *48-49*
Geocentric theory of solar system. *See* Earth-centered theory
George III, King, 172
Germanium bolometer, *72*, 73
Glycerol, 137
Goldstone, Calif., tracking station, *76-77*
Gondwanaland, 58
Granite, 36, *57*
Gravitation, force of, 14, 15, 83; and escape velocities, 84; Newton's law, 15, 24, 109
Great Red Spot, Jupiter, *155*-156, 159, 160, *161, 164-165*
Greek astronomy, 11-13, 14, *20-23*, 84
Greenhouse effect, 42, 43, 112, *114, 115*, 134

H

Haute Provence, France, observatory, *70-71*
Heat exchange, atmospheric, 42
Heliocentric theory of solar system. *See* Sun-centered theory
Helium: as component of Jupiter, 153, 154; as component of Saturn, 170; in Jupiter's atmosphere, 153, 155; in sun and stars, 35, 38
Herschel, Sir William, 172
Hevelius, Johannes, drawing of moon by, *85*
Hidalgo, asteroid, *135*
Hide, Raymond, 164
Hirzgarter, Matthias, engravings by, *119, 133*
Holloman Air Force Base, *78*
Hot springs, 38
Hoyle, Fred, 30
Hoyle-Alfvén hypothesis, *30-31*

Hudson Bay, astrobleme features, 88, *map* 89
Hydrocarbons, 39, 127
Hydrogen, as component of Jupiter, 153, 154, 157, 160, 166; as component of Saturn, 170; detection on planets, 68; in early earth atmosphere, 38, 39, 186; in early Mars atmosphere, 136; in earth atmosphere at present, 43; in Jupiter's atmosphere, 153, 155, 159, 166; metallic state under pressure, 154, 166; in Neptune's atmosphere, 183; in sun and stars, 35, 38; in synthesis of organic molecules, 39, 158, 159, 186

I

Ice ages, 93
Ikeya-Seki, comet, *168*
Imbrian Event, lunar history, *87*, 88
Infrared brightness temperature, 64
Infrared radiation, 42, 61, 65; absorption by water vapor and carbon dioxide, in atmosphere, 42, 79, 112, *113*; analysis by germanium bolometer, *72-73*; analysis of, in study of planetary atmospheres, 67, 73, 78, *79*; determination of planetary temperatures by, 64, *72-73*, 110, 111, *122*, 134, 157, 171; of planets, 42, 64, 70, 72, *113*; velocity of, 61; of Venus, 110, 111, 112, *122*; wavelength of, 42, *diagram* 66
Infrared window of atmosphere, 65, *diagram* 66
Insects, adaptability of, 137
Intelligence: and civilization, 178-179, 190; conditions for development of, 177, 190; survival value of, 177, 178
Interior characteristics of planets: and absence or presence of magnetic field, 36, 115, 136, 157; currents, 36, 37; of earth, 34-36, 37, 44, *56*, 57 (*see also* Earth core; Earth mantle); of earth, methods of study of, 34, *35*, 57; of Jupiter, 153, 154, 156, 157, 160, 166; of Mars, 136; of other planets, method of study of, 35; of Saturn, 171; of Venus, 115-116
Interplanetary distances, 180, *181*
Interplanetary dust, 80, 85
Interstellar matter, 153
Interstellar travel, 179
Io, Jovian satellite, 158, *163*
Ionization, 110-111
Ionosphere: of earth, 43, *graph* 56, 57; of Venus, 110-111, *115*
Iron, as component of planets, 34, 35, 36, 44, 115-116, 136

J

Jansky, Karl, 65
Jeans, Sir James, 28, 29
Jet Propulsion Laboratory, 76
Jodrell Bank, radio telescope, *69*
Johannesburg, South Africa, tracking station, 77
Johns Hopkins University, balloon-borne Venus project, *78-79*
Jovian planets, *11*, 173
Jupiter, 10, 13, *24-25*, 94, 153-159, 160, *161-167*, 171, 172; ammonia clouds, 153, 155, 164; in astrology, 11; atmosphere of, 153, 154-156, 160, *161*, *164-165*, 166; atmospheric composition, 153, 155, 159, 186; atmospheric pressure, 154, 155, 160; clouds of, 153, 154, 155, *161*, *164-165*; color, meaning of, 159; compared to stars, 156-157, 160; composition of, 153, 154; core of, 153, 154, 156, 157, 166; density of, 153; diameter of, 171; distance from earth, 160; distance from sun, 154; duration of year of, 160; effect on comets, 175; gravitation of, 154; Great Red Spot, *155*-156, 159, 160, *161*, *164-165*; heat emission of, 73, 156-157, 160; ice crystals in clouds, 155; lack of free oxygen and nitrogen, 155, 159; "life zone" of, 159, 173; magnetic field of, *157*, 166; mass of, 153, 166; near asteroid belt, 85, *135*, possible future of, 154; precipitation on, 155, 164; radiation belt around, 36, 66, 75, 154-155, *157*, 158, *161*, *166-167*; radio bursts, 158; radio emissions of, 75, *157*-158; radio storms, 158; Red Spot Hollow, 155; rotational period of, 153; satellites of, 61, 71, 152, 153, 158, *162-163*; size comparison, *11*, 153; spectroscopic analysis of light of, 70, *71*, 153, 155; speculations on life on, 153, *158*-159, 173, 180, 186; surface of, 154, 156, 166; symbol, *8*; telescopic observatinn of, 61, 70, *72-73*, 79, 153, 154, *161*; temperature above clouds, 73, 157, 171; temperature extremes, 153, 154, 155, 159, *166-167*, volume of, 153; water droplets in clouds of, 155, 159; water vapor in atmosphere of, 155; weather phenomena on, 155, 160; winds on, 154-155; "zones" of, 154-155
Jupiter simulator, creation of organic compounds in, 186, *187*
Juvenile water, 38

K

Kant, Immanuel, 26
Kant-Laplace hypothesis of origin of solar system, *26-27*, 28
Kepler, Johannes, 14, 15, 24, 25, 26
Kozyrev, N. A., 89
Kuiper, Gerard P., color map of Mars, *147*

L

Lalande 21185, planetary system, *table* 179
Land masses, *See* Continental drift; Continents
Laplace, Pierre Simon, Marquis de, 26, 27
Laurasia, 58
Lava: on earth, 36, 37; on moon, *86-87*, 88, 90, 96, 103
Lava flow, studies of, 104, *105*
Leverrier, Urbain Jean Joseph, 172-*173*
Lick Observatory, 94
Life, 137-138, 176-179, 190; adaptability of, 116-117, 136-137, 188; civilized, 178-179, 190; conditions propitious for, 9-10, 176-177, 188, 190; doctrine of convergence, 176-177; doctrine of divergence, 177; intelligent, 169, 177-179, 190; laboratory synthesis of, 39-40, 138 (*see also* Organic compounds); organic molecules as precursors of, *39-40*, *158-159*, 186, *187*
Life, extraterrestrial, 41, 138, 176-179, 180, 188; atmospheric "zones" of, 159, 173, 182, 183, *190-191*; improbable on Mercury, 170; improbable on Pluto, 174, 182, 183; on Jupiter, speculations on, 153, *158*-159, 173, 180; on Mars, speculations on, 131, 132, 133, 134-139, 140, *142-143*, 146, *148-149*, 150; microenvironments for, 138; on moon, speculations on, *90*, 92-93; on other planets, problems of detection of, 47, 48, 51, 53, 138, 180, *181*; outside solar system, probabilities of, 54, 169, 176-179, 190; possible form, *190-191*; question of "zones" on Neptune and Uranus, 173, 182, 183; on Saturn, speculations on, 173, 182, 183; space lab for detection of, 138-139, *186*; on Venus, speculations on, 111, 116, 128
Life on earth: adaptability of, 116-117, 136-137, 188; age of, 40, 177; basic chemical makeup of, 40, 137-138; carbon cycle, 41; civilization process, 178-179; and climate and seasons, *52-53*; conditions for, 9-10; early fossils, *41*, evolution of, *39*-41, 54, 177; intelligent, 177; microorganisms, 40, 116, 117, 137, *188*; ultraviolet radiation and, 39, 42; variety of, *54-55*
Light, visible, 61; emission by planets, 63, 64; and optical astronomy, 61-65; and photographic astronomy, 62-63, 64; spectroscopic analysis of, 63, *64*, *65*, *71*; spectrum, 63; velocity of, 61, 179; wavelengths of, 63, *diagram* 66
Lightning: as agent in creation of organic molecules, 159, 186, *187*; on Jupiter, 155, 159
Limonite, 136, 137
Lippershey, Hans, 61
Low, Frank, *72-73*
Lowell, Percival, 132, 140, 142; color map of Mars, *147*; Martian canals, map of, *142-143*; postulation of planet X (Pluto), 173
Lowell Observatory, Arizona, ultraviolet photography, *120*
Luna III, 102
Luna IX, *93*, 96, 102; pictures taken by, 68, 90, 91
Lunar eclipses, 11
Lunar laboratory, *106-107*
Lunar Orbiter II, 102; picture taken by, *103*
Lunar Orbiter III, 102; pictures taken by, *102*

M

M31, galaxy, *185*
Madrid, Spain, tracking station, 77
Magnetic field, cause of, 36, 157; detection of, 65-66, 74, 157; of earth, *36*, 43, 57, 85; of Jupiter, *157*, 166; lack of, on Mars, moon and Venus, 157; undetected on Saturn, 172
Magnetism, 36
Magnetopause, 43
Magnetosphere, *36*
Mantle, *See* Earth mantle
Mapping of planets, techniques of, *82*, 120, *121*
Mare Crisium (Sea of Crises), lunar feature, 88, *96*
Mare formation, *86-87*, 88-89
Mare Imbrium (Sea of Rains), lunar feature, 84, *86-87*, 88, *95*, *97*
Mare Nectaris, lunar feature, 88
Mariana Trench, *57*
Mariner II, Venus probe, *76-77*, 111, 115, *122-123*
Mariner IV, Mars probe, *80-81*, 133, 136, 144; closest approach to Mars, 134, 144; photographs of Mars, 47, 80, 131, 132, 134, 139, *144-145*
Mars, 10, 13, *24*, 33, 94, *130*, 131-139, 140, *142-151*, 172; in astrology, 11, *141*; atmosphere of, 80, 131, 132, 133-134, 135; atmosphere of, in early stages, 136; atmospheric composition, 134, 136; atmospheric pressure, 133; canal controversy, 131-132, 140, *142-143*, *145*; clouds of, 131, 132, 134, *143*; color of, 131, 136; color changes observed on, 53, 132-133, 134, *146*, *148-151*; color maps, *147*; core of, 136, 157; craters on, 80, 134-135, 144, *145*; deserts, 132, 133, 135, 136, 138; deserts, possibility of life in, 137; diameter of, 131; discovery of orbit and orbital speed of, 14, *25*; distance from earth, 44, *139*, distance from sun, 131; duration of year of, 133; dust covering of, 134, *150-151*; early history of, 135-136; erosion on, 135, 144, 150; highlands of, 139; lack of free oxygen, 133, 134, 136; lack of magnetic field, 136, 157; Mariner IV photographs of, 47, 80, 131, 132, 133, 134, 136, 139, *144-145*; mass of, 131; meaning of name, 140; meteorite impacts, 134-135; near asteroid belt, 85, *135*, oppositions of, *139*; orbit of, *25*, 131; polar ice caps, 50, 131, 132, 133, *146*, *149*, possibility of groundwater on, 138; radar studies of, 66, 139; rust theory of early history, 136; satellites of, 139; seasonal changes, 33, 131, 132-133, *146-151*; size comparison, *11*; speculations on life on, 131, 132, 133, 134-139, 140, *142-143*, 146, *148-149*, 150, 188; subsurface temperature, 134; surface features of, 80, 132-133, 134-135, 139, *144-151*; surface material, 134, 136; surface temperature, 134; symbol, *8*, *133*, Syrtis Major, and rock-shape theory, *133*; telescopic observation of, 62, 70, 71, 79, 131, *133*, *146*; tilt of axis of, 133; Voyager project, 80, 150; water scarcity on, 133, 134, 136; water vapor in atmosphere of, 134, 136; winds on, 134, 150
Mars jars (simulators), 137, *188*
Martian "cities," 140, *143*, Lowell's map, *142-143*
Martians of H. G. Wells, *137*
Mass of planets, determination of, 109
Menesz, Vening, 58
Mercury, 10, 13, *24*, 94, 169-170, 172; in astrology, 11; atmosphere of, 170; diameter of, 163, 169; difficulties of observation of, 169; distance from earth, 169; does not keep same face toward sun, 66, 74, 170; former hot-and-cold, sun-facing theory, 169-170; life improbable on, 170; phases of, *119*; radar studies of, 66, 74, 170; rotation of, 170; size comparisons, *11*, *163*; surface features of, 96, 170; symbol, *8*; temperature of, 73, 170
Mesopotamia, 10, 11
Mesosphere, 42, *graph* 56, 57
Meteorites: in asteroid belt, 135; and crater formation, 85, *86*, 87, *88*, *97*, *98-100*; on earth, 35, 85, 87-*88*, *map* 89, 99, 104, 135; impact speed and force, 86; on Mars, 134-135; on moon, 85-87, 89, 91, 97-99, 106, 135
Meteors, cometary, 175
Methane, as atmospheric component, 190; detection on planets, 68; in early earth atmosphere, 38, 39, 41, 186; in early Mars atmosphere, 136; in Jupiter's atmosphere, 155, 158, 159; in Neptune's atmosphere, 173; in Saturn's atmosphere, 171; in synthesis of organic molecules, 39, *158*-159, 186, *187*, in Uranus' atmosphere, 173
Microbiological planetary engineering, 116-117
Micrometeorites, 85, 91
Microorganisms, 40; adaptability of, 116-117, 137, *188*, early fossil, *41*
Microwaves, 61, 65; Jupiter's emission of, *167*; Saturn's emission of, 172; Venus' emission of, 110-111, *122*
Middle Ages, 12, 13
Milky Way, 75, *184*, detected planetary systems in, 176, *table* 179, number of planets in, 176, number of planets capable of supporting life, 54; number of stars in, 175, 184; size of, 184
Mizar, 61
Moho (Mohorovicic discontinuity), *57*
Mohorovicic, Andrija, *57*
Moon, 9, 83-93, 94, *95-103*; absence of surface water on, 85, 92, 96; albedo, 89; brightness of, 89-90, 94 172; caves on, 92; core of, 157, craterlets, *97*, craters, 84, 85-87, 88, 89, 91, 92, 95, *98-100*, 101, *102*, diameter of, 84, 169, dust covering, 91-96; escape velocity from, 84, formative period of, 86-87, future Astronauts' landings on, 83, 84, 92, *106-107*, geologic map of, *82* gravitational pull of, 11, 84, 94; highlands, 86, 99, history of, 85-89, Imbrian Event, 87, 88; keeps same face toward earth, 84; lack of atmosphere, 83, 84-85, 96, lack of magnetic field, 157; lack of wind and water erosion on, 84, 85, 86, 135; lava theory of mare formation, *86-87*, 88, life on, speculations, *90*, 92-93; Luna III probe, 102; Luna IX landing on, 68, *93*, 96; magnetic wake of, 158; maria (seas), 84, 85, *86-87*, 88-89, 92, *95-97*, 99; mass of, related to earth's mass, 84; meteorite impacts, 85-87, 89, 91, 97, *98-99*, 106, 135, mountains of, 83-84, 85, 87, *96*, *102*; orbit of, 14, 15; orbital speed of, 15, 163; origin of, 84; phases of, *17*; possibility of underground water, 92-93; radar studies of, 66, 91; radioactivity on, 88, 93; radio emissions of, 91; Ranger probes of, 91, Ranger IX photographs of, 67, 91-92; ray craters, *85*, *86-87*, *100*, 101; rills (clefts), *101*, *102*; rotation of, 102; 17th Century drawings of, *84*, *85*, shadows on, 83; slump pits on, 91-92; solar radiation on, 85, 106; spectroscopic analysis of, 63, 89, surface of, 66, 67, 80, 83-92, 94, *95-103*, 135; surface material, 89-91 96; Surveyor project, 67, 90, *104-105*; symbol, *8*, telescope observations of, *84*, *95-101*; temperatures, 83, 90; temperature changes on, 90-91, temperature measurement, 73; and tides of earth, 11; volcanism on, 85, *86*, 89, 96, 103; Zond III, 102
Moon vehicle, *106-107*
Moons of other planets. *See* Satellites, planetary
Morris, Elliot, *104*
Motion, planetary: early concepts of circular, 12, 13-14, *15*, *22-25*, elliptical, discovery of, 14, 24, *25*; momentum, 30-31; speeds, 24, *25*
Motion, proper vs. apparent, 176
Mount Palomar telescope, 62, *71*, 185
Mountain-building, *58*, 85
Mutation, 40, 177
Mythology, *10*, 16, *18-19*, 140, *141*, *175*

N

Nastapoka Island chain, 88
Navaho Indian astronomy, *13*
Naval Research Laboratory, Washington, D.C., 66
Nebular hypothesis of origin of solar system, 26, 30, 35; Hoyle-Alfven, *30-31*; Kant-Laplace, *26-27*, 28
Neptune, 10, 172-173, 182, *183*, atmosphere of, 173, 182; atmospheric composition, 173, 183; diameter of, 173, discovery of, 71, 172-173; distance from sun, 173; lack of oxygen, 182; question of life zone on, 173, 182, 183, orbit of, 173; rotational period (day), 173; satellites of, *183*; size comparison, *11*; spectroscopic studies of, 183; temperatures of atmosphere of, 173, 182
Newton, Sir Isaac, 15, 24, 109
Nicholson, Seth B., 125
Nickel-iron, earth core, 44
Nitrogen, in earth atmosphere, 38, *39*; in Martian atmosphere, 134, in Venus' atmosphere, 116
North America, astroblemes in, *map* 89
Northern lights, 158
Nuclear reactor, *189*, survival of bacteria in, 117, *188*
Nucleic acids, 40-42, 116, 137
Nucleotides, synthesis of, 40
Nut, Egyptian goddess, *10*

O

Ocean of Storms (Oceanus Procellarum), lunar feature, 88, 96
Ocean ridge, *58*
Ocean trenches, *57*, *58*
Oceans of earth, 34, 41-42; average depth, 34; deepest point, *57;* evolution of life in, 39-41; formation of basins, 37, *58;* mass of, related to total earth mass, 38; significance of, 41-42
Optical astronomy, 61-65, 68, *70-73;* and space observatories, 66-67
Optical (visible) window of atmosphere, 64-65, *diagram* 66
Orbits of planets, 14, 24, *25*
Organic compounds, creation of early, *39*-40, *158*-159; laboratory synthesis, 39, 186, *187*
Origin of planets: catastrophic theory, 34-35; dust-and-gas-cloud theory, 35, 44; Hoyle-Alfvén hypothesis, *30-31;* Jeans's tidal theory of, *28-29;* Kant-Laplace nebular hypothesis, *26-27*, 28
Outgassing: earth, 38; moon, 84-85
Owens Valley observatory, Caltech, *75*
Oxygen: in carbon cycle, 41; in earth atmosphere, 39, 41, 42; in oceans, 41; transformation into ozone, *diagram* 38, 42
Ozone, *diagram* 38, 42, 79
Ozone layer, 42, *graph* 56, 57

P

Perihelion, *25*
Phases of planets, *119*
Philolaos, universe of, 20, *21*
Phobos, Martian satellite, 139
Photodissociation, 39, 43
Photographic astronomy, 62-63, 64; ultraviolet, *120*
Photosynthesis, 40-41; essential requirements for, 116
Pickering, William H., 173
Pioneer satellites, 36
Pisces, constellation, 23
Planetary motion. *See* Motion, planetary
Planetary systems other than solar system, 31, 169, 175-176, 184; detection techniques, 176, 179; in Milky Way, 176, *table* 179; probabilities of life in, 54, 169, 176-178, 190; question of advanced civilization, 178-179, 190
Planets: arrangement of, in solar system, 10, 13, 24; in astrology, 11; catastrophic theory of formation of, 34-35; distances from earth, determining, 68; early history of, 35; Jovian vs. terrestrial, *11;* number of, 9, 10, 44; orbital speeds of, 24, *25;* orbits of, 14, 24, *25;* origin of (*see* Origin of planets); outside solar system, 31, 175-176 (*see also* Planetary systems); satellites of (*see* Satellites, planetary); 17th Century illustrations, *8*, *62;* size comparison, *11;* sizes of, and Jeans's hypothesis, *28-29;* symbols for, *8*
Plant life: evolution of, 40-41; and seasons, *52-53;* variety of, *54-55*
Pluto, 10, 173-174, 182, *183;* atmosphere improbable on, 182; discovery of, 29, 71, 173, 183; distance from earth, 77; distance from sun, 174; duration of year of, 173; lack of oxygen, 182; life improbable on, 174, 182, 183; size comparison, *11;* telescopic observation of, *183;* temperature of, 73, 183
Potassium, 35, 36
Prevailing westerlies, 155
P (primary) waves, earthquake, 34, *35*
Proper motion, 176
Proteins, 39, 116, 137
Protons, solar, 80, 91, 101
Pseudonomas bacteria, *188*
Ptolemaeus crater, lunar feature, 98
Ptolemaic system, 12, 13; planetary motion in, *23*
Ptolemy, Claudius, 12, 23

R

Radar, planet research by, 66, 68, *69*, 74, 75; Mars, 66, 139; Mercury, 66, 74, 170; moon, 66, 91; Venus, 66, 113, 114-115, 120, *121;* wavelength used, 65
Radiation: atmospheric absorption of, *diagram* 38, 42-43, 57, 65, *diagram* 66-67, 79, 85; kinds of, 61, *diagram* 66-67; of planets, 42, 64, 67, 74; solar, 38-39, 42-43, 85. *See also* Gamma rays; Infrared radiation; Light; Radio waves; Ultraviolet radiation; X-rays
Radiation belts: earth, Van Allen, *36*, 43, *graph* 56, 57, 66, 157, 158; Jupiter, 36, 66, 75, *157*, 158, *166-167;* undetected on Saturn, 172
Radio astronomy, 65-66, 68, *74-75*, 110, 114, 170; and space observatories, 67
Radio messages, alien civilizations, 179
Radio telescopes, 65-66, 68, *69*, *74-77;* on space satellites, 67; world's largest (Arecibo), *74-75*, 170
Radio tracking stations, for space probes, 77
Radio waves, 61, 65; emission by Jupiter, 75, *157*-158; emission by moon, 91; emission by planets, 67, 74; emission by Saturn, 172; emission by Venus, 110-111, 114, *115;* transmission around earth, 43, 65; velocity, 61; wavelengths, 61, 65, *diagram* 66-67
Radio window of atmosphere, 65, *diagram* 66-67
Radioactive components of planets, 35, 36
Rain forest, Brazil, *52-53*
Ray craters, *85*, *86-87*, *100*, 101
Red dwarfs, 157
Red Sea: and continental drift, 37; source of color of, 159
Red Spot Hollow, Jupiter, 155
Reducing atmosphere, 38-39
Reducing gases, 38, 41, 43, 136
Relativistic travel, 179
Resolving power, of eye, 61
Retrograde rotation, 113, *117*
Revolutional momentum, 30-31
"On the Revolutions of the Heavenly Bodies," Copernicus, 13
Rotation of planets, direct vs. retrograde, 113, *117*
Rotational momentum, sun and planets, *30-31*

S

St. John, Charles, 125
St. Lawrence, Gulf of, astrobleme features, 88
San Andreas Fault, 37
Satellites, planetary, 10, 83; Callisto, *163;* Deimos, 139; Europa, *163;* Ganymede, *163;* Io, 158, *163;* of Jupiter, 61, 71, 152, 153, 158, *162-163;* of Mars, 139; of Neptune, *183;* Phobos, 139; of Saturn, 163, *172*, 183; Titan, 183; Triton, *183;* of Uranus, *183*. *See also* Moon
Saturn, 10, 13, *24*, 94, 170-172, *182-183;* in astrology, 11; atmospheric composition, 171; atmospheric pressure, 171; clouds of, 171; composition of, 170; core of, 171; density of, 170-171; diameter of, 171; duration of year of, 171; gravitation of, 172; lack of oxygen, 182; mass of, 170-171; in Ptolemaic system, *23;* question of life zone on, 173, 182; question of magnetism and radiation belt, 172; radio emissions of, 172; rings of, 170, 171-172, *182-183;* rotational period (day) of, 171; satellites of, 163, *172*, 183; size comparison, *11;* symbol, *8;* telescopic observation of, 171; temperatures of atmosphere, 171, 182; temperature measurement, 73; wind bands of, 171
Schiaparelli, Giovanni, 132, 142; *canali* maps of, *142*, *143*
Science fiction, *90*, 92, *137*, 180
Sea of Clouds, lunar feature, 84
Sea of Crises. *See* Mare Crisium
Sea of Rains. *See* Mare Imbrium
Seasons: cause of, 10-11, *132;* no change on Venus, 120; of earth, 10-11, *52-53*, 133; of Mars, 33, 131, 132-133, *146-151*
S (secondary) waves, earthquake, 34, *35*
Sediment, 37, 57
Seismic waves, 34, *35*, 57
Seismogram, 34
Seismology, 34, 57
Seismometer, 34; ancient Chinese, *34*
Selenites, of H. G. Wells, *90*, 92
Selenography, 85
Shklovsky, Iosif S., 139
Shoemaker, Eugene, *82*
Shooting stars, 175
Shu, Egyptian god, *10*
Silicates, as component of planets, 35, 36
61 Cygni, planetary system, *table* 179
Sizes of planets: comparison of relative, *11;* earth, 34; and Jeans's hypothesis, *28-29;* Jupiter, 153, 171; Mars, 131; Mercury, *163*, 169; Neptune, 173; Pluto, 174; Saturn, 171; Uranus, 173; Venus, 109
Sky, *32;* cause of blue hue, 33, 48
Slump pits, on moon, 91-92
Solar eclipses, 11, *12*
Solar system, 9, 175; age of, 9, 35; comparative sizes of bodies in, *11;* diameter of, 9, 184; exploration by spaceships (*see* Spacecraft exploration of solar system); extent of classical, *8*, 172; history of concepts of, 9-15, 16, *17*, *18*, *20-25;* Hoyle-Alfvén hypothesis of origin of, *30-31;* interplanetary distances, 180, *181* (*see also individual planets*); Jeans's tidal theory of origin of, *28-29;* Kant-Laplace nebular hypothesis of origin of, *26-27*, 28; origin and formation of, 9, 16, 26, *30-31*, 34-35, 44; 17th Century engraving, *8*
Solar systems, other. *See* Planetary systems
Solar wind, *36*, 85
Solis Lacus, Martian "city," 140
Soviet space probes, 121. *See also* Luna III; Luna IX; Zond III
Space observatories, 66-67
Space travel, 179
Spacecraft exploration of solar system, 9, 68, 76-77, 80, 91-92, 93, 121; Luna III, 102; Luna IX moon landing, 68, *93*, 96; Mariner II Venus probe, *76-77*, 111, 115, *122-123;* Mariner IV Mars probe, 47, *80-81*, 131, 132, 133, 134, 136, 139, *144-145;* Ranger probes of moon, 91; Ranger IX moon probe, 91-92; search for life, laboratory for, 138-139, *186;* Surveyor, moon project, *104-105;* Voyager, Mars project, 80, 150; Zond III, 102. *See also* Earth, views of, from space
Spectrometer, 67
Spectroscope, 63, 70, *71*, *78*
Spectroscopic analysis, 63, *64*, *65*, *71;* and Doppler shift, 113; of Jupiter, 70, *71*, 153, 155; of moon, 63, 89; of Neptune, 183; of Venus, 67, *78*, 110, 112, 125, 126
Spectrum. *See* Electromagnetic spectrum; Light, spectrum
Speed of light, 61, 179
Speeds, orbital, 24, *25*
Stars, 175-176; composition of, 38, 153; distance of nearest, 9, 179; double, *190;* nearest single, 176; number in Milky Way galaxy, 175, 184; origin of, 175; planets of, 175-176 (*see also* Planetary systems); proper motion, 176; red dwarfs, 157; rotation of, 31; spectroscopic analysis of, 63; thermonuclear reactions in, 156
Stereoscopic viewer, *105*
Straight Wall, lunar feature, *101*
Sumerian mythology, *18-19*, 140
Sun, 9, 10, 175-176, *184;* composition of, 38; diameter of, 184; motion of, 184; origin and history of, *26-27*, 35, 156; planet sizes compared to, *11;* in Ptolemaic system, *23;* radiation of, 38-39, 42-43, *diagram* 66-67, *85;* rotation of, *30-31;* symbol, *8;* thermonuclear reactions in, 35, 156. *See also* Solar eclipses; Solar wind
Sun-centered theory of solar system: ancient Greek, 12, *21;* Copernicus, 13-14, 16, *24-25;* Kepler, 14, 24, *25*
Supernova of 1054, 13
Surface characteristics: of early earth, 35-36, 58, *map* 59; of earth, at present, 33-34, 36-37, 41-42, *57*, *map* 59, *114;* of earth, changes in, 36-37, *58*, *maps* 59, 85; of earth, possible future, 37, 58, *map* 59; of Jupiter, 154, 156, 166; of Mars, 80, 132-133, 134-136, 139, *144-151;* of Mercury, 96, 170; of moon, 66, 67, 80, 83-92, 94, *95-103;* other planets, methods of study of, 63-64, 66, 68, *69*, *71-73*, 80, 96; photographs of, interpretation problems, *50-51;* of Venus, 66, 73, 80, 110-112, 114-115, *128-129*
Surface dustiness, detection of, 73
Surveyor, moon probe project, 67, *104-105*
Symbols of planets, *8*
Syrtis Major, Martian feature, *133*

T

Taylor column, 156, *165*
Technical civilization, 178-179, 184, 190
Telescopes, 68, *70-73;* balloon-borne, 67, *78-79;* basic optical principle of, 62; development of, *60*, 61-62; limited by bad seeing, 64, 67; on space satellites, 67; spacecraft-borne, 80; world's largest (Mount Palomar), 62, *71*, 185. *See also* Radio telescopes
Temperate zone, seasonal changes, 52, *53*
Temperature(s): atmospheric, other planets, measuring, 64, 73, 74; of earth atmosphere, 42; of earth core, 36, 56; at earth surface, 41-42, *114;* infrared brightness, 64; of Jupiter, 153, 154, 155, 159, *166-167;* of Jupiter, above clouds, 73, 157, 171; Martian subsurface, 134; Martian surface, 134; of Mercury, 73, 170; of moon, 83, 90-91; of Neptune's atmosphere, 173, 182; of Pluto, 73, 183; of radio sources, detection of, 65-66, 68, 74, 91; of Saturn's atmosphere, 171, 182; surface, other planets, measuring, 64, 68, 71, *72-73*, *115;* of Uranus' atmosphere, 173, 182, 183; of Venus' atmosphere, 111; of Venus' cloud deck, 110, 122; of Venus, subsurface, 114; of Venus, at surface, 66, 73, 110-112, 114, 122, 128
Terrestrial planets, *11*
Thales, universe of, *20-21*
Thermonuclear reactions, stellar, 35, 156
Thermosphere, *graph* 56, 57
Thorium, 35, 36
Tidal theory of origin of solar system, *28-29*
Tides, cause of, 11
Time, shrinking of, at high speed, 179
Titan, Saturnian satellite, 183
Tombaugh, Clyde, 173
Tracking stations, for space probes, 77
Trade winds, 155
Travel, interstellar, 179
Trenches, ocean, *57*, *58*
Triton, Neptunian satellite, *183*
Tropical rain forest, *52-53*
Tropopause, 42
Troposphere, 42, *graph* 56, 57
Tundra, Canadian, *52*
Tycho Brahe, 14, *15;* study of comets, *174*, 175
Tycho crater, lunar feature, 86, 91, *100*

U

Ultraviolet photography, Venus, *120*
Ultraviolet radiation, 38, 61; absorption of, by atmosphere, *diagram* 38, 42-43, 57, 79; agent in creation of organic molecules, *39*-40, *158*-159, 186; danger to present earth life forms, 39, 42; on moon, 85, 106; photodissociation by, 39; in planets' spectra, 67; velocity, 61; wavelength, *diagram* 66
Union Carbide Company, 188
United States East Coast, view from space, *46*, 47
United States space probes. *See* Mariner II; Mariner IV; Ranger IX; Surveyor; Voyager
Universe, history of concepts of, 9-15, 16, *17*, *18*, *20-25*
University of Arizona, studies of planet temperatures, *72-73*
University of Illinois, radio telescope, *75*
Uranium, 35, 36
Uranus, 10, 27, 172-173, 182, *183;* atmosphere of, 173, 182, 183; atmospheric composition, 173; clouds of, 173; diameter of, 173; discovery of, 71, 172; distance from sun, 173; lack of oxygen, 182; orbit of, 172; question of life zone on, 173, 182, 183; rotation of, 113, 173; satellites of, *183;* size comparison, *11;* temperature of atmosphere of, 173, 182, 183; wind bands of, 173
Urcontinent, 36, 37

V

Vacuum welding, 90
Van Allen, James, 36
Van Allen radiation belts, *36*, 43, *graph* 56, 57, 66, 157, 158
Velocities, orbital, 24, *25*
Velocity of light, 61, 179
Venera IV, Soviet Venus probe, 67, 111
Venus, 10, 13, *24*, 33, 109-117, 118, *119-129*, 172; absence of seasonal change, 120; in astrology, 11; atmosphere of, 78, 109-112, *115*, 116, 125, 126-127, 128; atmospheric composition, 112, 125, 128; atmospheric pressure on, 114, 115, 120, 128; Babylonian record of movements of, *108;* balloon probes of, 67, *78-79*, 112; brightness of, 109; carbonated (soda) sea theory of, 110, 118, *126;* cloud deck of, 78, 79, 109, 110, 112, 113, *115*, *120*, 128; colonization from earth, 116-117; color of, 109; cool vs.

hot hypotheses, 110-111, *115*; core of, 115, 157; density of, 109; desert theory of, 118, *125*; diameter of, 109; distance from sun, 109; duration of day on, 120; duration of year on, 113; dust covering, 114, 115; erosion on, *128-129*; greenhouse effect, 112, 114, *115*, 117; ice crystals in clouds, 79, 110, 112, 115, 128; infrared radiation of, 110, 111, 112, *122*; interior of, 115-116; ionosphere of, 110-111, *115*; Johns Hopkins project, *78-79*; lack of free oxygen, 125; lack of magnetic field, 115, 122, 157; mapping of, 120, *map* 121; Mariner II probe, *76-77*, 111, 115, *122-123*, mass of, 109; mountains of, 66, 114-115, *121*; nearest distance from earth, 33; oil ocean theory of, 110, 118, *127*; phases of, 61, *62*, 71, 109, 118, *119*, *120*; possibility of existence of water on, 114, 116, 128; radar studies of, 66, 113, 114-115, 120, *121*; radio emissions of, 110-111, 114, *115*; rotation of, 110, 113, *117*, 120, *121*; Russian space probe of 1966, 121; size comparison, *11*, spectroscopic analysis of atmosphere of, 67, *78*, 110, 112, 125, 126; speculations on life on, 111, 116, 128; subsurface temperature, 114; surface features of, 66, 80, 114-115, *121*, *128-129*, surface materials, 114, 115, 116; surface temperature of, 66, 73, 110-112, 114, 122, 128; swamp theory of, 118, *124*; symbol, *8*; telescopic observation of, 62, 70, 71, *78-79*, 109, *120*; temperature of atmosphere of, 111; temperature of cloud deck of, 110, 122; tint of sky on, 115; ultraviolet photographs of, *120*; water droplets in clouds, 115, 116, 128; water vapor on, 67, 79, 112, 125, 128; winds on, 115, *120*, 125, 128
Visible (optical) window of atmosphere, 64-65, *diagram* 66
Volcanism: on earth, 36, 38, 57, 58; on moon, 85, *86*, 89, 96, 103
Voyager, Mars probe project, 80, 150
Vulcan, planet, Leverrier's erroneous postulation of, *173*

W

War of the Worlds, The, Wells, *139*
Wargentin crater, lunar feature, 88
Water: absence on moon's surface, 85, 92-93, 96; droplets, in Jupiter's clouds, 155, 159; droplets, in Venus' clouds, 115, 116, 128; juvenile, 38; photodissociation of molecules of, 39, 43; presence of and life, 47; scarcity on Mars, 133, 134, 136; in synthesis of organic molecules, 39, 159, 186; Thales' concept of, 20; on Venus, possibility of existence of, 114, 116, 128
Water vapor: in earth atmosphere, 38; in earth atmosphere, as barrier to parts of spectrum, 42, 65, 67, 79; and greenhouse effect, 42, 112; in Jupiter's atmosphere, 154, 159; in Martian atmosphere, 134, 136; in synthesis of organic molecules, 159; on Venus, 67, 79, 112, 125, 128
Weather satellite photographs, *46-47*
Wells, H. G.: Martians of, *137*, Selenites of, *90*, 92
Winds: on Jupiter, 154-155, on Mars, 134, 150; primary cause of, 42, 155, on Saturn, 171, system on earth, 155; on Venus, 115, *120*, 125, 128
Wobble, detection of planetary systems by, 176, 179
Wood, R. W., 63
Woomera, Australia, tracking station, 77

X

X-rays, 61, 85; velocity, 61, wavelength, *diagram* 66

Y

Yardangs, *128-129*

Z

Zond III, moon probe, 102

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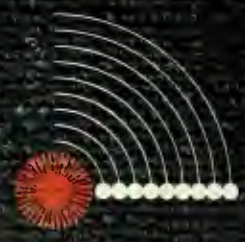
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